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PRELIMINARY EVALUATION OF HYDROFOIL BASE METALS AND COATING SYS--ETC(U)
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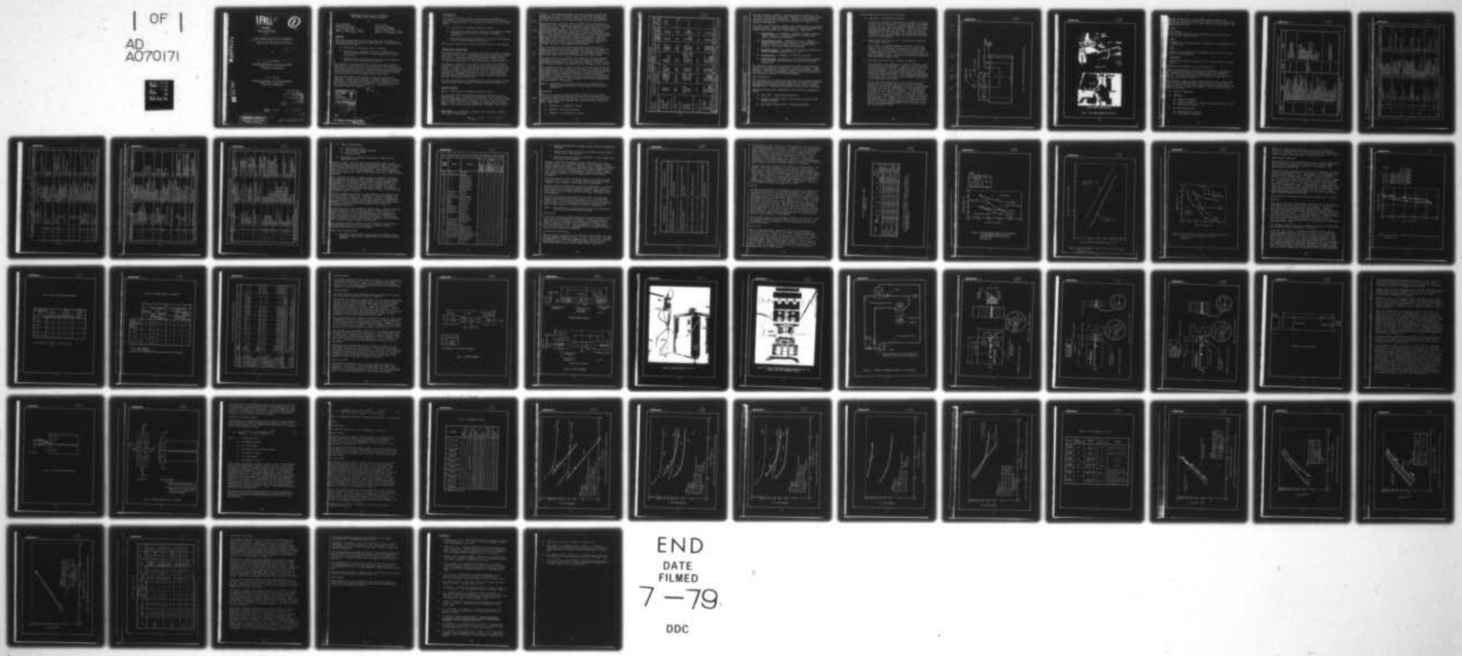

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(6) PRELIMINARY EVALUATION OF HYDROFOIL BASE METALS AND COATING SYSTEMS,

(12) 60p.

BY

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ENCLOSURE (1)

"PRELIMINARY EVALUATION OF HYDROFOIL
BASE METALS AND COATING SYSTEMS"

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ABSTRACT

The program was prepared to investigate the performance of material systems for hydrofoil applications. Three tasks were identified as follows:

a) Selection of candidate metallic alloys.

b) Evaluation of corrosion protection techniques for those candidate metallic alloys requiring corrosion protection.

c) Determination of the fatigue and fracture characteristics of selected material systems.

The candidate base metals were reviewed for the hydrofoil application. Four materials were chosen for this evaluation. They were 17-4PH and 15-5PH stainless steels, HY 130 steel and Ti 6Al-2Cb-1Ta-1Mo titanium. Fracture and corrosion fatigue data are being obtained on these materials as part of an on-going program and the available data is reported.

Since the HY type alloys require a corrosion protective coating, a screening evaluation of coating systems has been conducted. Four coating systems have been selected for further testing including their effect on the corrosion fatigue and fracture properties of the HY 130. Details of the screening tests are reported.

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INTRODUCTION

The Hydrofoil Material Evaluation program was prepared to investigate the performance of material systems for hydrofoil and strut applications. The program consisted of three primary tasks:

a) Selection of candidate metallic alloys.

b) Evaluation of corrosion protection techniques for those candidate metallic alloys requiring corrosion protection.

c) Determination of the fatigue and fracture characteristics of selected material systems.

This report covers the first six months effort on the program.

SUMMARY AND CONCLUSIONS

Candidate materials were reviewed for potential usage as hydrofoil struts and foils. Four materials were chosen for further evaluation. They were 17-4PH and 15-5PH stainless steels, HY 130 steel, and titanium 6Al-2Cb-1Ta-1Mo. Fracture and corrosion fatigue data are being obtained on these materials.

In addition, because the HY type alloys require a corrosion protective coating, an evaluation of coating systems was conducted. To date, four coating systems have been selected for further evaluation including their effect on the fracture and corrosion fatigue properties of the HY 130. These coating systems are: Hypalon, PRC 1581-17, and Astrocoat 8000 each over wire-metallized aluminum plus their respective primers, and PRC 1581-M with primer only.

No final conclusions or recommendations have been made in this report because this program is being extended through 1973.

PROGRAM DETAILS

TASK 1 - Selection of Candidate Metallic Alloys

The Hydrofoil Materials Research Program reported by Ling-Temco-Vought, Inc. in 1965 (1)* concluded that HY 130, Ti 7Al-2Cb-1Ta (superseded by Ti 6Al-2Cb-1Ta-1Mo), and 17-4PH castings were suitable for hydrofoil usage. A report issued by the NSRDC in April 1972, (2) reviewed the advantages and disadvantages of four metal systems (aluminum, titanium, nickel and

*The number in parentheses indicates the reference listed at the end of this report.

steel). This study concluded that the following alloys have potential for foil and strut usage; HY 130 (HY 180 was considered an excellent material but required more development), 17-4PH, Ti 6Al-4V, Ti 6Al-2Cb-1Ta-1Mo, Inco 718 and Rene'41.

A Boeing paper, "Decision Paper - PHM Foil Array Materials Selection" (3) discussed the selection of an alloy for the PHM foils and struts. The final choice was made between HY 130 and 17-4PH stainless steel. The HY 130 is field repairable with as-welded weld properties essentially equal to base metal properties, but the alloy requires a corrosion protective coating. The 17-4PH is not field repairable in that all welds must be heat treated but does not require any coating. The final PHM choice was 17-4PH based on service experience with the Tucumcari and the lack of a coating requirement. Boeing has also selected 15-5PH (a slight chemistry modification of 17-4PH) for use on the Commercial Hydrofoil.

The U.S. Navy has had considerable experience with the HY series of alloys and has used HY 80 for foils on the Highpoint and Plainview. HY 130 was selected for the Mod 1 retrofit foils and struts for the Highpoint. Considerable difficulties have been experienced with the coatings for these boats.

The approach for the selection of materials for this program included a review of the literature and past history and a qualitative evaluation of the material systems. Table 1 shows the selection factors considered and the ratings of the alloys.

The choice of HY 130, 17-4PH, 15-5PH and Ti 6Al-2Cb-1Ta-1Mo for the program was based on Boeing's interest and usage of the PH stainless steels, the USN interest in HY 130, and the potential advantages of the Ti 6Al-2Cb-1Ta-1Mo. Because the HY 130 requires corrosion protection to realize the full potential of the alloy, a coating system evaluation program was included as Task 2 of the program. Such coatings could also be applicable to other metals, if desirable.

TASK 2 - Evaluation of Corrosion Protection Techniques for Those Candidate Metallic Alloys Requiring Corrosion Protection

Background

The HY 130 low-alloy steel presently proposed for hydrofoil strut/foil assemblies requires a corrosion protection system to provide suitable corrosion-fatigue life and erosion protection. Three basic protective systems were considered for investigation. These were:

a) Cathodic, or impressed current.

b) Passive, or barrier coating.

c) Galvanic, or sacrificial coating.

Table 1: FOIL/STRUT MATERIAL SELECTION

POTENTIAL CANDIDATES	ASSESSMENT FACTORS							SELECTION FOR EVALUATION
	FABRICABILITY	CORROSION RESISTANCE	COST	REPAIRABILITY	STRUCTURAL WEIGHT	SUITABILITY FOR SERVICE LIFE		
						SHORT	LONG	
STAINLESS STEELS:								
17-4PH △1	GOOD	GOOD △3	BASELINE	POOR	BASELINE	YES	YES	17-4PH
15-5PH	GOOD	GOOD △3	BASELINE	POOR	BASELINE	YES	YES	15-5PH
22-13-5	GOOD	EXCELLENT	HIGHER	EXCELLENT	HIGHER	NO	YES	
300 SERIES	GOOD	GOOD △3	LOWER	EXCELLENT	HIGHER	NO	NO	
TITANIUM ALLOYS:								
6Al-2Cb-1Ta-1Mo	POOR	EXCELLENT	HIGHER	POOR	LOWER	YES	YES	6Al-2Cb-1Ta -1Mo
6Al-4V	POOR	EXCELLENT	HIGHER	POOR	BASELINE	NO	YES	
ALLOY STEELS:								
HY-80	EXCELLENT	POOR △4	LOWER	EXCELLENT △5	HIGHER	NO	NO	
HY-100	EXCELLENT	POOR	LOWER	EXCELLENT	HIGHER	NO	NO	
HY-130	GOOD	POOR	LOWER	EXCELLENT	BASELINE	YES	YES △6	HY-130
HY-180	GOOD	POOR	LOWER	GOOD	LOWER	YES △7	NO	
9Ni-4Co	GOOD	POOR △4	LOWER	EXCELLENT △5	LOWER	YES	NO	
NICKEL BASE ALLOYS:								
INCO 718	POOR	EXCELLENT	HIGHER	POOR	LOWER	NO	YES	
ALUMINUM ALLOYS:								
5000 SERIES	EXCELLENT	GOOD	LOWER	EXCELLENT	HIGHER	YES	NO	
6000 SERIES	GOOD	GOOD	LOWER	GOOD	HIGHER	YES	NO	
2219	GOOD	POOR △4	LOWER	GOOD	HIGHER	NO	NO	
2024	GOOD △2	POOR △4	LOWER	GOOD △8	HIGHER	NO	NO	
7000 SERIES	GOOD △2	POOR △4	LOWER	GOOD △8	HIGHER	NO	NO	

△1 BASELINE MATERIAL △2 NOT WELDABLE △3 SUBJECT TO CREVICE CORROSION △4 REQUIRES COATING
△5 REQUIRES COATING REPAIR PROCEDURE △6 DEPENDENT ON SATISFACTORY COATING △7 REQUIRES ADDITIONAL DEVELOPMENT
△8 REQUIRES MECHANICAL FASTENING AND JOINING

The first system, cathodic, was considered too difficult to control in the present application because of the aluminum hull and high velocity boat operation. Therefore, this system of corrosion protection was considered beyond the scope of the present investigation.

The other two protective systems were investigated as sprayable coating systems. Several general types of coating systems were commercially available for investigation. These were:

a) <u>Elastomeric</u> - For example - Neoprene rubber, urethane rubber, Hypalon (a chlorosulfonated polyethylene), and/or flexible polyurethanes.

b) <u>Metal/Metal Filled</u> - Examples are wire or plasma sprayed metals such as aluminum or zinc, Sermetel (an aluminum-filled inorganic material), metal filled primers, and metal-filled polyurethanes.

c) <u>Epoxy-Polyamide</u> - An example is a Wisconsin Protective Coating Company product-Plasite 7133.

d) <u>Thermoplastic</u> - Examples are Teflon coatings.

e) <u>Thermosetting</u> - Examples are the polyurethane coatings such as those used presently for exterior airplane protection.

The following tests for evaluating the corrosion and erosion protection of coating systems were intended to screen a large number of commercially available coatings and primers. From the many a few high performance coatings were to be chosen for more intensive testing in a future program.

Test Procedures

The available HY 130 steel was 3/16 inch thick and was prepared for coating application by grit blasting to bare metal with a subsequent methyl ethyl ketone (MEK) solvent wipe to remove residual grit. Coatings were applied following grit blasting.

Coating specimens were subjected to the following schedule of tests:

a) Tape Test - Preliminary Screening

b) Scratch and Impact Test - Preliminary Screening and Damage Standard

c) Salt-Water Erosion Test - Primary Screening

△5 REQUIRES COATING REPAIR PROCEDURE △6 DEPENDENT ON SATISFACTORY COATING △7 REQUIRES ADDITIONAL DEVELOPMENT
△8 REQUIRES MECHANICAL FASTENING AND JOINING

A brief description of each test follows:

a) Tape Test - Preliminary Screening

A series of parallel lines were cut through the coating down to the substrate and a second series at 45 degrees to the first. A strip of tape was applied across the scribes and the tape subsequently removed in one abrupt motion perpendicular to the panel. The area was then examined for lifted coating. The amount of coating removed by the tape was taken as a qualitative measure of how well the coating would perform during the salt-water erosion testing.

b) Impact Test and Scratch Test - Preliminary Screening and Damage Standard

Two scribes connecting opposite corners of the test panel were cut through the coating to the metal substrate. The coating was then impacted at the scribe intersection with a loading of 60 in-lb using the Gardner Impact Tester. If the coating did not spall or peel the samples were considered for further testing in the salt-water erosion test.

c) Salt-Water Erosion Test - Primary Screening

The salt-water test apparatus, shown in Figures 1 and 2 accommodated four specimens. Salt-water at 3.5% NaCl solids was fed through 1/2" diameter brass nozzles from a central chamber. A forty horsepower motor drove a 200 gallon/minute centrifugal pump rated at 350 foot head to provide velocities of salt-water impingement to a maximum of about 60 knots. The specimens were bolted in position at a forty-five degree forward inclination to the impinging jet stream.

The HY 130 steel specimens (3/16 inch thick x 2-1/2 inches wide x 8 inches long) coated with candidate materials, scribed and impacted per test b, were bolted into position and the salt-water velocity adjusted to 52 knots (or 110 psi gage reading). A standard test duration was four days, or 96 hours. A test designated by A, e.g., 3A, represents a time less than 96 hours but of sufficient duration to indicate a coating failure mode. The temperature rise in the salt water was minimized by a simple cooling coil immersed in the reservoir section through which cold water was circulated. The equilibrium temperature of the salt water was approximately 106^{o}F.

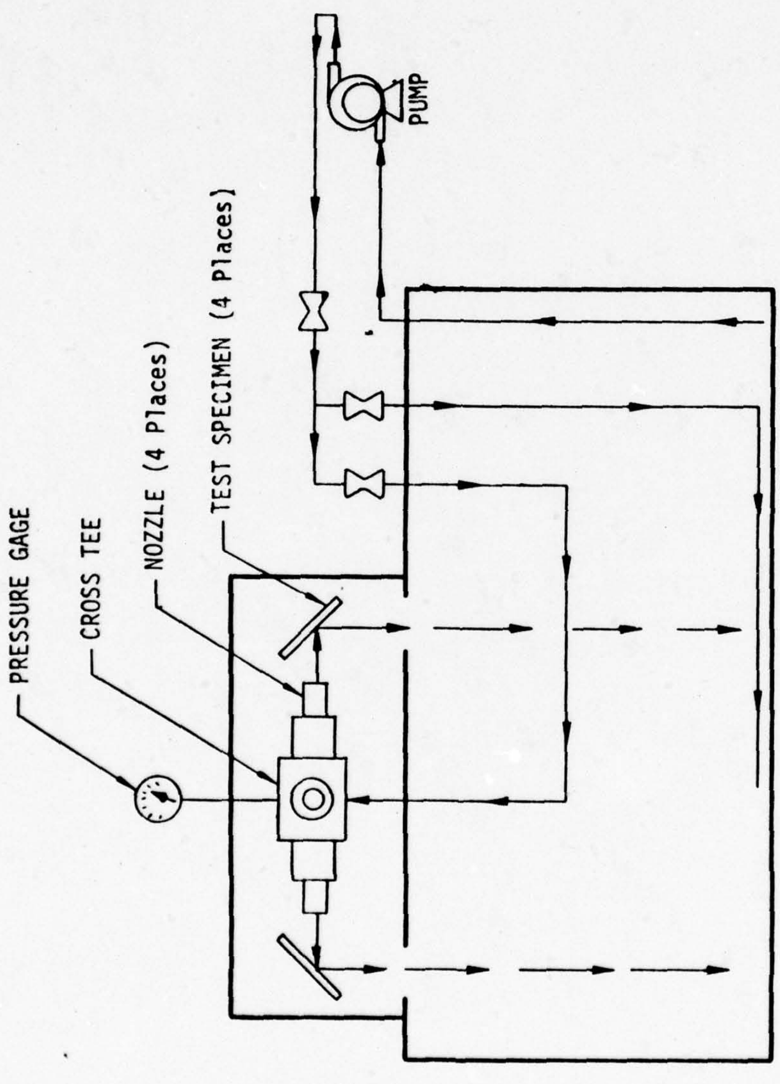
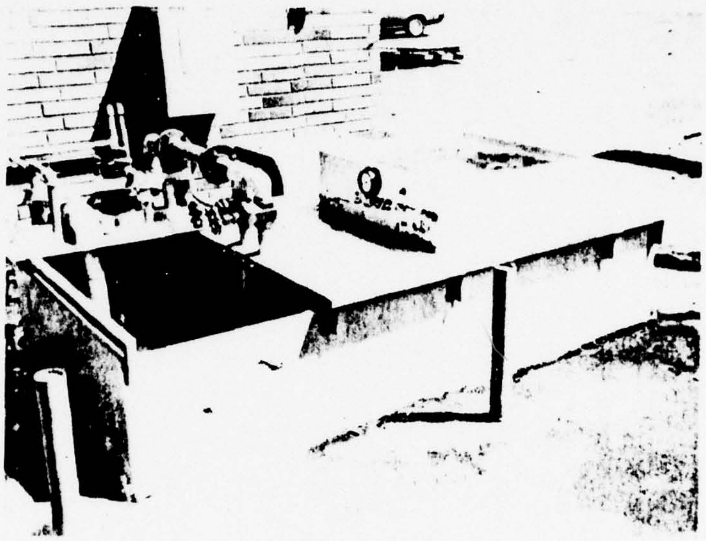
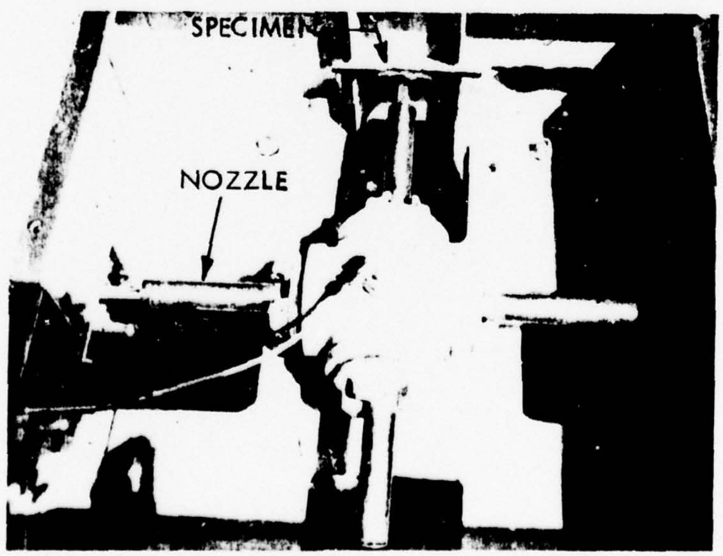


Figure 1: SCHEMATIC OF SALT WATER EROSION TEST FACILITY



OVERALL VIEW



VIEW OF NOZZLES AND SPECIMENS

Figure 2: SALT WATER EROSION TEST FACILITY

After the erosion test, the specimens were examined for evidences of erosion, corrosion and adhesion loss. Ratings of the coatings from good to very poor were given according to the following definitions.

Good

No evidence
(1) of the coating and/or coating-primer peeling away or
(2) of pits and/or erosion

Fair

Maximum of 3/8-inch peeling of coating at X-intersection of scribe lines

Poor

Loss of 5 to 20 percent (1-4 square inches) of the coating and/or coating primer.

Very Poor

Loss of more than 20 percent of the coating and/or coating-primer.

Discussion of Salt-Water Erosion Test Results

A total of 110 specimens coated with 62 different coatings has been evaluated using the salt-water erosion test apparatus. The coatings used, listed by chemical type, are given in Table 2. The materials tested plus detailed primer and overcoat data are given in Table 3.

Those coatings rated as Good, and/or Good-to-Fair, on the basis of the visual inspection after erosion testing, were further rated to select four candidates for testing in the fracture and corrosion fatigue property evaluation. The following rating factors were used:

a) Erosion Resistance

b) Adhesion

1) Overcoat to primer
2) Primer to Metal
3) Primer to Undercoat (metalized aluminum and/or zinc)
4) Undercoat to Metal

c) Corrosion Prevention

1) Contributed by coating
2) Contributed by primer

Table 2: COATINGS USED IN SALT-WATER EROSION SCREENING TESTS BY CHEMICAL TYPE [1]

CHEMICAL TYPE	COATING NAME
ELASTOMERIC	ASTROCOAT 8000 (BLACK) ASTROCOAT 8001 (YELLOWING WHITE) BRIDGE PAD RUBBER (DUROMETER 60) DAPCO 1200 AL ETHYLENE-PROPYLENE SYN. RUBBER HYPALON HYPALON PLUS GLASS WOOL N-29, GACO (SPRAYABLE NEOPRENE) N-55/N-83, GACO (SPRAYABLE NEOPRENE) NATURAL RUBBER (HI-TEAR) (DUROMETER 61) NEOPRENE (DUROMETER 49) NEOPRENE (DUROMETER 58) NEOPRENE WX (CONDUCTIVE) (DUROMETER 78) PRC 1527 (POLYURETHANE RUBBER) PRC 1581-M (SPRAYABLE POLYURETHANE) SILICONE (DC 92-009) U-6521, GACO (SPRAYABLE URETHANE)
EPOXY	FUSECOTE (ELECTROSTATICALLY SPRAYED) PETERSON NO. 200 PLASITE 7133 (EPOXY-POLYAMID) STEELCOTE EPO-LINE 164
METAL/ METAL FILLED	ALUMINUM 5456-0 ALUMINUM 6061-T-651 ALUMINUM, PLASMA SPRAYED, 3-5/8-10 MILS, WITH/WITHOUT SEALER ALUMINUM, WIRE METALLIZED, 3-5/8-10 MILS, WITHOUT SEALER ALUMINUM-FILLED POLYURETHANE, 3M XA5932/5076 DIMETCOTE 3 + D-3 (INORGANIC ZINC) SERMETEL W (AL FILLED) SERMETEL 249/433 STEEL, HY 130 STEEL, 15-5PH H-1050 STEEL, 17-4PH H-1050 TITANIUM 6AL-4V TITANIUM 8AL-1MO-1V ZINC, WIRE METALLIZED, 3-5/8-10 MILS, WITHOUT SEALER
THERMOPLASTIC	TEFLON, FEP TEFLON, FEP, PLUS ALUMINUM OXIDE FLAME SPRAYED PRIMER (WITHOUT SEALER) TEFLON, TFE
THERMOSETTING (POLYURETHANE ENAMEL)	ANDREW BROWN A 1250 ANDREW BROWN A 1340-66 CERMET 4-0-78/4-Y-78 DÉ SOTO 701 BLACK DE SOTO 792 WHITE DEXTER 4-W-89 DEXTER 7-W-27 DEXTER 7-W-53 FINCH (BOEING SPECIFICATION 10-60 & 10-72) POLANE L, SHERWIN-WILLIAMS PRC 1140 PRC 1580 STERLING U-1347 USP 91-W-3 XA 5932/5076
MISCELLANEOUS	GLIDFLAKE 296-W-218 (GLASS-FILLED POLYESTER) VINYL PLASTISOL (UDYLITE)

[1] SOME COATINGS WERE TESTED IN VARIOUS COMBINATIONS OF THICKNESSES AND WITH VARIOUS PRIMER SYSTEMS.

1 SOME COATINGS WERE TESTED IN VARIOUS COMBINATIONS OF THICKNESSES AND WITH VARIOUS PRIMER SYSTEMS.

Table 3: SALT WATER EROSION TESTS

TEST NO.	SAMPLE NO.	PRIMER	OVERCOAT	RESULTS OF TEST
1	32	DEFT (ZINC CHROMATE EPOXY) BMS 10-53	FINCH POLYURETHANE BMS 10-60 TYPE I	POOR
	34	DITTO	FINCH URETHANE BMS 10-72 TYPE I	POOR
	39	GACO N-15	GACO HYPALON (5 MILS) BMS 10-51 TYPE II	GOOD
	45(48)	CERMET 4-G-14	CERMET POLYURETHANE 4-0-78/4-Y-78	VERY POOR (ADHESION)
2	1	PRODUCTS RESEARCH 1533	PRODUCTS RESEARCH 1527 POLYURETHANE	POOR
	11	DUPONT 856-301	FEP TEFLON (DUPONT 856-200) NO SEALER	VERY POOR (VISIBLE CORROSION)
	15	NONE	PLASMA SPRAYED ALUMINUM (8-10 MILS) NO SEALER	GOOD
	17	NONE	DITTO WITH SEALER	GOOD (SEALER - POOR)
3	12	DUPONT 851-204	TFE TEFLON (DUPONT 851-205) NO SEALER	GOOD
	22	NONE	WIRE METALLIZED ALUMINUM (8-10 MILS) NO SEALER	GOOD
	24	NONE	WIRE METALLIZED ZINC (8-10 MILS) NO SEALER	GOOD
	52	URETHANE COMPATIBLE, BMS 10-79	POLYURETHANE DESOTO BAC 792 WHITE, BMS 10-60 TYPE II	VERY POOR (ADHESION)
3A 1	76	EPOXY, BMS 10-11 TYPE I	POLYURETHANE, PRODUCTS RESEARCH 1580	GOOD
	77	DITTO	DEXTER 4-W-89	FAIR
	78	DITTO	USP 91-W-3	GOOD
	79	DITTO	ALUMINUM FILLED, 3M XA5932/5076	VERY POOR (ADHESION)
	80	DITTO	POLYURETHANE, ANDREW BROWN A 1340-66.	FAIR
	81	DITTO	STERLING U-1347	POOR
4	54	EPOXY, BMS 10-53	POLYURETHANE, FINCH GRAY 643-3-9, BMS 10-72	POOR
	58	URETHANE COMPATIBLE	POLYURETHANE, DESOTO, BAC 701 BLACK, BMS 10-60 TYPE II	GOOD TO FAIR
	72	CERMET 4-G-14	POLYURETHANE, CERMET 4-0-78/ 4-Y-78	VERY POOR (ADHESION)
	74	NONE	SERMETEL W (ABRADED) BOEING APPLIED	GOOD
4A	82	NOT KNOWN (VENDOR APPLIED)	POLYURETHANE, ASTROCOAT 8000 (ON ALUMINUM)	VERY POOR (ADHESION)

1 PRELIMINARY RESULTS ONLY. SEE TEST 6 FOR FINAL TEST.

Table 3: SALT WATER EROSION TESTS (Continued)

[illegible]	SAMPLE NO	PRIMER	OVERCOAT	RESULTS OF TEST
5	5	CHEMLOK 205/234	EPDM (SYN. RUBBER) 1/2" THICK BMS 1-50	GOOD
	13	FLAME SPRAYED Al Al_2O_3/DUPONT 856-301	BOECLAD TEFLON, DUPONT 856-200 (WITHOUT SEALER)	GOOD
	29	BROLITE P-1500 ZINC FILLED	FINCH URETHANE, BMS 10-72 (TYPE I)	VERY POOR (INCOMPATIBLE PRIMER)
	50	PRC 420	POLYURETHANE, PRC 1140 (YELLOW/WHITE)	GOOD TO FAIR
6	84	EPOXY, BMS 10-11 TYPE I	POLYURETHANE, USP 91-W-3,	POOR
	86	DITTO	DEXTER MIDLAND 4-W-89	GOOD
	88	DITTO	PRC 1580	VERY POOR
	91	DITTO	DEXTER MIDLAND 7 W-27 TEFLON FILLED POLY.	GOOD
6A	93	EPOXY, BMS 10-11 TYPE I	ALUMINUM FILLED, 3MXA5729/ XA5079	VERY POOR (OVERCOAT ADH. TO PRIMER)
	95	GACO E-5322	GACO U-6521, 16 MILS	VERY POOR (PRIMER ADHESION)
	96	DITTO	DITTO (37 MILS)	DITTO
7	108	NONE	SERMETEL W/SERMETEL 596, VENDOR APPLIED	GOOD
	109	NONE	SERMETEL 249/SERMETEL 433 VENDOR APPLIED	VERY POOR (EROSION RESISTANCE)
	110	ASTROCOAT 8200	POLYURETHANE, ASTROCOAT 8000 35 MILS, VENDOR APPLIED	GOOD TO FAIR (SUBSTRATE CORROSION)
	111	DITTO	DITTO (63 MILS)	GOOD
8	14	NONE	PLASMA SPRAYED ALUMINUM, 3-5 MILS, NO SEALER	GOOD
	16	NONE	DITTO (METCO AP PHENOLIC SEALER)	GOOD TO FAIR
9	21	NONE	WIRE METALLIZED ALUMINUM 3-5 MILS, NO SEALER	GOOD
	23	NONE	WIRE METALLIZED ZINC (3-5 MILS) NO SEALER	GOOD
9A	98	GACO E-5322 (EPOXY) GACO N-15	GACO N29-N39 (NEOPRENE) (90 MILS)	GOOD
	107	GACO N-15	GACO U-6521 (URETHANE RUBBER)	VERY POOR (ADHESION TO PRIMER)
	123	LAMINAR X 500 4-G-14	LAMINAR X-500 7-W-53 (TEFLON)	POOR
	125	ASTROCOAT 8200	ASTROCOAT 8000 32 MILS (BOEING SPRAY APPLIED)	FAIR TO POOR
10	127	ASTROCOAT 8200	ASTROCOAT 8000 120 MILS (BOE.APPLIED-CAST)	GOOD
	128	ASTROCOAT 8200	DITTO (55 MILS - SPRAYED)	POOR (ADHESION TO PRIMER)
10A	99	GACO N-15	GACO N-29 (NEOPRENE)	GOOD
	104	GACO E-5322	GACO U-6521 (URETHANE RUBBER)	VERY POOR (PRIMER ADHESION)

10A	104	GACO E 5322	GACO U 6521 (URETHANE RUBBER)	VERY POOR (PRIMER ADHESION)

Table 3: SALT WATER EROSION TESTS (Continued)

TEST NO.	SAMPLE NO.	PRIMER	OVERCOAT	RESULTS OF TEST
11	2	CHEMLOK 205/220	NEOPRENE, BATCH 814, .228 IN-THICK, D58	GOOD
	3	CHEMLOK 205/220	NEOPRENE BATCH 788, ABOUT .2 INCH THICK, D49	GOOD
	117	WIRE METALLIZED ZINC + CHEMLOK 205/220	BRIDGE PAD RUBBER, 88 MILS THICK, D60	POOR
	132	WIRE METALLIZED ALUMINUM + CHEMLOK 205/220	NEOPRENE WX (CONDUCTIVE), 80 MILS THICK, D78	GOOD
12	116	WIRE METALLIZED ALUMINUM + CHEMLOK 205/220	BRIDGE PAD RUBBER, 87 MILS THICK, D60	GOOD TO FAIR
	129	BMS 10-11 TYPE I	HYPALON (GACO) + ONE LAYER OF GLASS WOOL CLOTH (90 MILS)	VERY POOR 1
	130	DITTO	DITTO + ANOTHER LAYER OF GLASSWOOL CLOTH (82 MILS)	VERY POOR 1
	134	CHEMLOK 205/234	SYN. RUBBER (BMS 1-50), 157 MILS THICK, D65	GOOD
13	4	CHEMLOK 205/220	NATURAL RUBBER (HI-TEAR), ABOUT .2 INCH THICK, D61	GOOD
	136	WIRE METALLIZED ALUMINUM	GLIDFLAKE 296-W-218	FAIR TO POOR
	138	GRIT BLAST ONLY (FORMERLY USED SPECIMEN)	UNCOATED HY 130	VERY POOR
	139	GRIT BLAST ONLY	UNCOATED HY 130	VERY POOR
14	140	—	UNCOATED TITANIUM 6A1-4V	GOOD
	141	—	UNCOATED TITANIUM 8A1-1MO-1V	GOOD
	142	BMS 10-11 TYPE I	ANDREW BROWN A 1250 (POLYURETHANE)	FAIR TO POOR
	143	NOT KNOWN (VENDOR APPLIED)	FUSECOTE GREEN (20-25 MILS) (ELECTROSTATICALLY SPRAYED EPOXY) (DIAGONAL CUTS MADE WITH KNIFE)	GOOD
15	144	NOT KNOWN (VENDOR APPLIED)	FUSECOTE GREEN (20-25 MILS) ELECTROSTATICALLY SPRAYED EPOXY (DIAGONAL CUTS MADE WITH BAND SAW)	GOOD
	146	—	UNCOATED ALUMINUM 6061-T-651	GOOD (SL. EROSION BUT NO CORROSION)
	149	—	UNCOATED 17-4PH H-1050	GOOD (SL. DISCOLORATION)
	150	—	UNCOATED 15-5PH H-1050	GOOD (SL. DISCOLORATION)
16	154	BMS 10-11 TYPE I	HYPALON (BMS 10-51 TYPE II) (4.4 MILS THICK)	GOOD
	155	DITTO	DITTO (8.3 MILS THICK)	GOOD (SL. WAVING ACTION ON COATING)
	156	DITTO	DITTO (ABOUT 12 MILS THICK)	GOOD (DITTO)
	30A	WIRE MET. ZINC + BMS 10-11 TYPE 1	DITTO (ABOUT 8 MILS THICK)	FAIR TO GOOD (CORR. OF ZINC ALONG DIAGONAL CUTS)
17	147	—	UNCOATED ALUMINUM 5456-0	GOOD (SL. EROSION BUT NO CORROSION)
	28	WIRE MET. AI + BMS 10-11 TYPE I	HYPALON (BMS 10-51 TYPE II) (THIN COATING, THICKNESS NOT KNOWN)	FAIR TO GOOD
	29A	DITTO	DITTO (ABOUT 12 MILS)	FAIR (CENTRAL AREA ERODED)
	31A	WIRE MET. ZN + BMS 10-11 TYPE I	DITTO (ABOUT 12 MILS)	POOR (EROSION OF HYPALON + CORROSION OF ZN)

1 VERY POOR AS ORIGINALLY COATED BUT GOOD AFTER ALL MATERIAL ERODED AWAY EXCEPT FOR ABOUT 4 MILS.

Table 3: SALT WATER EROSION TESTS (Continued)

TEST NO.	SAMPLE NO.	PRIMER	OVERCOAT	RESULTS OF TEST
18	157	PLASITE 7155 (PHENOLIC)	PLASITE 7133 (EPOXY-POLYAMID)	FAIR TO GOOD
	164	———	STEELCOTE EPO-LINE 164 (XYLENE SOLVENT USED)(10 MILS) EPOXY	VERY POOR (VERY BRITTLE)
	167	———	DITTO (MEK SOLVENT)	VERY POOR (VINYL ERODED + AI CORRODED)
	25	WIRE METALLIZED AI (3-5 MILS)	METCO CLEAR VINYL SEALER	VERY POOR (VINYL ERODED + AI CORRODED)
19	26	WIRE METALLIZED ZN (3-5 MILS)	METCO CLEAR VINYL SEALER	VERY POOR (VINYL ERODED)
	168	117 WASH PRIMER + GACO N-18 PRIMER	GACO N-55 + GACO N-83 (SPRAYABLE NEOPRENE)	VERY POOR (ADHESION TO WASH PRIMER)
	173	DAPCO 7012	DAPCO 1200 AL (POLYURETHANE)	VERY POOR (ADHESION TO PRIMER)
	175	BMS 10-11 TYPE I	PETERSON NO. 200 (EPOXY)	FAIR TO GOOD (CENTRAL IMPACT AREA ERODED)
20	177	WILLIAMS POLANE PRIMER	POLANE L (POLYURETHANE) 12 MILS	VERY POOR (EROSION)
	185	ASTROCOAT 8200	ASTROCOAT 8000 (POLYURETHANE) 60 MILS	GOOD
	190	GACO N-18	GACO N-55 + GACO N-83	VERY POOR (ADHESION TO PRIMER)
	193	———	DIMETCOTE 3 + D-3 CURING SOLN.	VERY POOR (UNUSUAL REACTION PATTERN)
20A	182	STB 10-7	PRC 1581-M	VERY POOR (ADHESION TO PRIMER)
	195	STB 10-7	PRC 1581-M	VERY POOR (ADHESION TO PRIMER)
	198	ASTROCOAT 8200	PRC 1581-M	GOOD
	203	BMS 10-11 TYPE I	PRC 1581-M	VERY POOR (ADH. TO PRIMER)
20B	135	CHEMLOK 205/234	EPDM (BMS 1-50)	VERY POOR (ADH. TO PRIMER)
	174	BMS 10-11 TYPE I	PETERSON 200 (EPOXY)	GOOD (12 DAY EXPOSURE)
	185*	ASTROCOAT 8200	ASTROCOAT 8000	GOOD (13 DAY EXPOSURE)
	189	GACO N-18	GACO N-55 + N-83	VERY POOR (ADH. TO PRIMER)
21	212	DC 4094	SILICONE, DC 92-009	GOOD TO FAIR (FINGER PEELABLE)
	214	NONE	ASTROCOAT 8001 (YELLOWING WHITE)	VERY POOR (ADHESION)
	219	W-629 (POST CURE AT 300F, 1 HR.)	VINYL PLASTISOL (UDYLITE) POST CURE @ 350F, 1 HR.	GOOD
	220	PR 1533 (POST CURE AT 180F, 1 HR.)	POLYURETHANE, BMS 8-81 (POST CURE AT 180F, 4 HRS.)	GOOD
22**	213	DC 4094	SILICONE, DC 92-009	GOOD TO FAIR (FINGER PEELABLE)
	215	NONE	ASTROCOAT 8001 (YELLOWING WHITE)	VERY POOR (ADHESION)
	218	W-629	VINYL PLASTISOL (UDYLITE)	GOOD
	222	PR 1533	POLYURETHANE, BMS 8-81	GOOD
23**	197	ASTROCOAT 8200	PR 1581-M	GOOD
	205	GACO N-15	GACO N-29	FAIR (EROSION RESISTANCE)
	210	GACO N-18	GACO N-55/N-83	POOR (ADHESION & BASIC EROSION RESISTANCE)
	224	ASTROCOAT 8200	GACO N-55/N-83	POOR (DITTO)

* SAME SAMPLE AS 20-185 BUT WITH EXTENDED EXPOSURE.
** A CENTER-SECTION ONE INCH (1") SQUARE CUT OUT PRIOR TO TESTING.

d) Ease of Application

   1) Simple Spray/Paint
   2) Electrostatic Spray Required
   3) Post Cure Required
   4) Vulcanization

e) Repairability (assumed from original application experience only)

Rated in Table 4 are the twenty-nine coatings which in the original erosion testing were rated as Good and/or Good-to-Fair. The columns representing Erosion Resistance, Adhesion, Corrosion Prevention, and Ease of Application were scored on the basis of 1 to 5, with 1 being superior. The column representing Repairability was rated on the basis of 1 to 3, with 1 being superior.

For a rating of 6 and 7, representing the superior coatings, the candidate coating was easy to apply, adhesion and erosion resistance were excellent and no repairability problems were anticipated. An excellent example of a coating with a low numerical rating was the Hypalon, with the BMS 10-11 Type 1 epoxy primer. This material was easy to apply, was erosion resistant during the 96-hour salt-water erosion testing and was considered easy to repair.

Several coatings were rated as only marginal even though superior in erosion resistance. Sermetel W (either specimen 4-74 or 7-108) with a rating of 9 was such a coating. Resistance to the salt-water erosion testing was superior but because of requisite post-cure application temperatures and similar difficulties in repairability the coating was only given an intermediate rating.

At the high end of the numerical rating scale, representing the poorest coatings, was the PRC 420 with a rating of 12. As shown in Table 4, even though application and repairability were rated superior, the erosion resistance and adhesion as well as primer corrosion prevention were poor. This coating would, therefore, not be considered a candidate in the fracture and corrosion fatigue property evaluation.

Four coating systems from the listing in Table 4 were chosen as candidates for future fracture and corrosion fatigue property evaluation with HY 130 steel.

These four coatings were:

- Astrocoat 8000 (a black rain-erosion elastomeric polyurethane) coated over a wash-primer over wire metalized aluminum

** A CENTER-SECTION ONE INCH (1") SQUARE CUT OUT PRIOR TO TESTING.

Table 4: COATING SYSTEMS RATED FOR THE FRACTURE AND CORROSION FATIGUE PROGRAM

EROSION TEST SAMPLE	PRIMER	OVERCOAT	RATING: SALT WATER EROSION RESISTANCE	RATING: ADHESION	RATING: COATING/PRIMER CORROSION PREVENTION	RATING: EASE OF APPLICATION	RATING: REPAIRABILITY	RATING: TOTAL OF RATINGS
16-154	EPOXY	HYPALON	1	1	2	1	1	6
20A-198	ASTROCOAT 8200	PRC 1581-M	1	1	2	1	1	6
9-21	——	W.M.AL(3-5 MILS)	1	1	1	2	2	7
3-22	——	W.M.AL(8-10 MILS)	1	1	1	2	2	7
8-14	——	P.SPR.AL(3-5 MILS)	1	1	1	2	2	7
2-15	——	P.SPR.AL(8-10 MILS)	1	1	1	2	2	7
9-23	——	W.M.ZN(3-5 MILS)	1	1	1	2	2	7
3-24	——	W.M.ZN(8-10 MILS)	1	1	1	2	2	7
17-28	W.M.AL+EPOXY	HYPALON	1	1	1	2	2	7
1-39	GACO N-15	HYPALON	1	1	3	1	1	7
10-127	ASTROCOAT 8200	ASTROCOAT 8000	1	1	2	1	2	7
19-175	EPOXY	PETERSON NO. 200	2	1	2	1	1	7
6-86	EPOXY	DEXTER 4-W-89	2	2	2	1	1	8
6-91	EPOXY	DEXTER 7-W-27	2	2	2	1	1	8
5-13	DUPONT 856-301	FEP TEFLON	1	1	1	3	3	9
18-157	PLASITE 7155	PLASITE 7133	3	2	2	1	1	9
9A-98	GACO E5322/N15	GACO N-29	3	1	3	1	1	9
4-74	——	SERMETEL W	1	1	1	3	3	9
7-108	——	SERMETEL W/596	1	1	1	3	3	9
4-58	URETHANE COMP.	DESOTO 701 BLACK	3	2	3	1	1	10
3-12	DUPONT 851-204	TFE TEFLON	1	1	3	3	3	11
12-134	CHEMLOK 205/234	EPDM	1	1	3	3	3	11
11-2	CHEMLOK 205/220	NEOPRENE, DUR. 58	1	1	3	3	3	11
11-3	CHEMLOK 205/220	NEOPRENE, DUR. 49	1	1	3	3	3	11
11-132	W.M.AL+CH.205/220	NEOPRENE WX, DUR. 78	1	1	3	3	3	11
12-116	W.M.AL+CH.205/220	BRIDGE PAD RUBBER, DUR. 60	1	1	3	3	3	11
13-4	CHEMLOK 205/220	NAT. RUBBER, DUR. 61	1	1	3	3	3	11
14-143	——	FUSECOTE EPOXY	1	1	3	3	3	11
5-50	PRC 420	PRC 1140	3	3	4	1	1	12

- Hypalon coated over an epoxy primer over wire metalized aluminum

- Products Research 1581-M (an elastomeric polyurethane) coated over a wash primer

- Products Research 1581-M coated over a wash primer over wire metalized aluminum

Astrocoat 8000 was developed by Olin Corporation as a rain erosion coating for airplane radomes. As a coating for salt-water erosion resistance, it has proved to be equally effective. Former application techniques involved hours of applying about 1 mil at a time with several hours of curing between coats. But a recent change in formulation by Olin Corp. has rendered the coating relatively easy to apply with no associated "bubbling."

The Gaco Hypalon coating performed best as a relatively thin coating of 4 to 8 mils. At greater thicknesses the coating tended to show "waving" under salt-water impingement.

Products Research 1581-M was originally developed as a sealant but has proved to have the necessary properties to perform quite well as an erosion resistant coating. Application was very simple with no "bubbling" effects often associated with polyurethanes.

The four coating systems chosen for fracture and corrosion fatigue evaluation are given in Table 5 with overcoat and primer data. The two most significant factors in the selection of these four from among the superior coatings listed in Table 4 were erosion resistance and ease of application.

TASK 3 - Determination of the Fatigue and Fracture Characteristics of Selected Material Systems

Background

A review of existing fatigue and fracture data was made at the time this test program was developed. Particular attention was given to data showing the influence of aqueous environments on fatigue strength, stress corrosion cracking, and cyclic flaw growth rate. Some information was uncovered on all four materials to be investigated and a summary of this is given in the following paragraphs.

15-5PH and 17-4PH Steel

The main sources of data for 15-5PH and 17-4PH steels were The Boeing Company, NSRDC and Armco. Carter, et al, (4), (5) have investigated the fracture toughness, K_{IC}, and stress corrosion threshold, K_{ISCC}, (in 3.5% NaCl solution) of both alloys. They conducted the K_{ISCC} tests under freely corroding

Table 5: DETAILS OF COATING SYSTEMS SELECTED FOR THE FRACTURE AND CORROSION FATIGUE PROGRAM

COATING NAME AND TYPE	PRIMER NAME AND TYPE
ASTROCOAT 8000: A Black Rain Erosion Elastomeric Polyurethane	Wire Metallized Aluminum Plus ASTROCOAT 8200 Wash -Primer
HYPALON (GACO): An Elastomeric Chloro-Sulfonated Polyethylene	Wire Metallized Aluminum Plus FINCH Epoxy Primer
PRC 1581-M: An Elastomeric Polyurethane	ASTROCOAT 8200 Wash-Primer
PRC 1581-M: An Elastomeric Polyurethane	Wire Metallized Aluminum Plus ASTROCOAT 8200 Wash-Primer

conditions and with 7075-T6 Al sheet clamped to the specimens to provide galvanic conditions. A summary of the results from these investigations is given in Table 6. The results show that coupling of 7075-T6 alloy to 17-4PH (H900) and 15-5PH (H900) reduces by approximately 40% the threshold stress intensity below which crack growth does not occur. Other studies (6) have shown this to be the result of hydrogen liberation at the stainless steel cathode. On the other hand, specimens in the H1000 condition showed significantly improved K_{ISCC} values, and the 15-5PH was immune to cracking.

Fatigue data are available for 15-5PH and 17-4PH steels. For example, The Boeing Company (7) has fatigue tested 17-4PH plate in air under fully reversing uniaxial loads; NSRDC (8) has tested 17-4PH plate material in air and Severn River water under fully reversing flexural loads; and Armco (9) has tested 15-5PH billet material in air under tension-tension uniaxial loads. The results of the NSRDC investigation is presented in Figure 3. It shows that the fatigue strength of 17-4PH is significantly reduced in a salt water environment. No corrosion fatigue data was uncovered for 15-5PH.

HY-130

A large volume of data is available on the HY steel material. HY 130 has a plane strain fracture toughness, K_{IC}, which is estimated (10) to be in excess of 250 ksi-in$^{1/2}$. Sandoz (11) recently collected and reviewed existing K_{ISCC} data on HY 130. This data was for the most part invalid but the range of K_{ISCC} was from 90-130 ksi-in$^{1/2}$. J.M. Barson, et al, (12), (13) has evaluated the cyclic flaw growth characteristics of HY 130 in air and a 3% NaCl solution. He used the DCB type specimen with a K_I range of 15-70 ksi-in$^{1/2}$, the air cyclic load rate was 60 cpm while 6 cpm was used for salt water tests. The air flaw-growth rates fell into a band which is characteristic of steel material. As shown in Figure 4, the salt water accelerated the flaw growth rate by approximately 2.5 times for the entire stress intensity range tested.

Air and salt water, R = -1, fatigue data for HY 130 taken from the Aerospace Metals Handbook (14) is shown in Figure 5. It is apparent that this material is very sensitive to the salt water environment.

Ti 6-2-1-1

The U.S. Navy has been responsible for the development of Ti 6Al-2Cb-1Ta-1/.8 Mo and is the primary source of information on this alloy. Huber et al, (15), summarized NRL fracture data for base metal (and welds) of Ti 6-2-1-1/.8. Using 1" thick plate for bend-bar K_{IC} tests and cantilever beam specimen K_{ISCC} tests they obtained fracture values of K_{IC} = 117 and K_{ISCC} = 98 ksi-in$^{1/2}$ (both invalid). In a recent NRL report (16) the fracture toughness for this material is estimated to be in the range of 150 to 240 ksi-in$^{1/2}$ based on dynamic-tear test (DTT) results.

Table 6: FRACTURE DATA ON PH STEELS
Reference 4 & 5

MATERIAL	HEAT TREATMENT	F_{ty} (Ksi)	F_{tu} (Ksi)	e (%)	K_{Ic} ($Ksi\text{-}In^{1/2}$)	K_{ISCC} ($Ksi\text{-}In^{1/2}$) FREELY CORRODING	K_{ISCC} ($Ksi\text{-}In^{1/2}$) COUPLED TO 7075-T6
17-4PH (Air Melted)	H 900	176.5	194.6	14	51.5	51.5(2)	28.4
	H 1000	157.9	162.2	15	119.0(1)	119.0(2)	91.2
15-5PH (Air Melted)	H 900	175.0	195.7	16	96.8(1)	80.0 ± 2.0	46.5
	H 1000	157.9	161.6	16	114.0(1)	114.0(2)	114.0(2)
15-5PH (Vacuum Melted)	H 900	174.9	191.5	14	74.5	55.8 ± 3.8	<40.7
	H 1000	157.8	162.9	15	120.0(1)	120.0	120.0(2)

(1) TEST DID NOT MEET ASTM REQUIREMENTS FOR VALID K_{Ic} DETERMINATION

(2) NO STRESS CORROSION CRACK GROWTH AT STRESS-INTENSITY LEVELS BELOW APPROXIMATELY 85% K_{Ic}

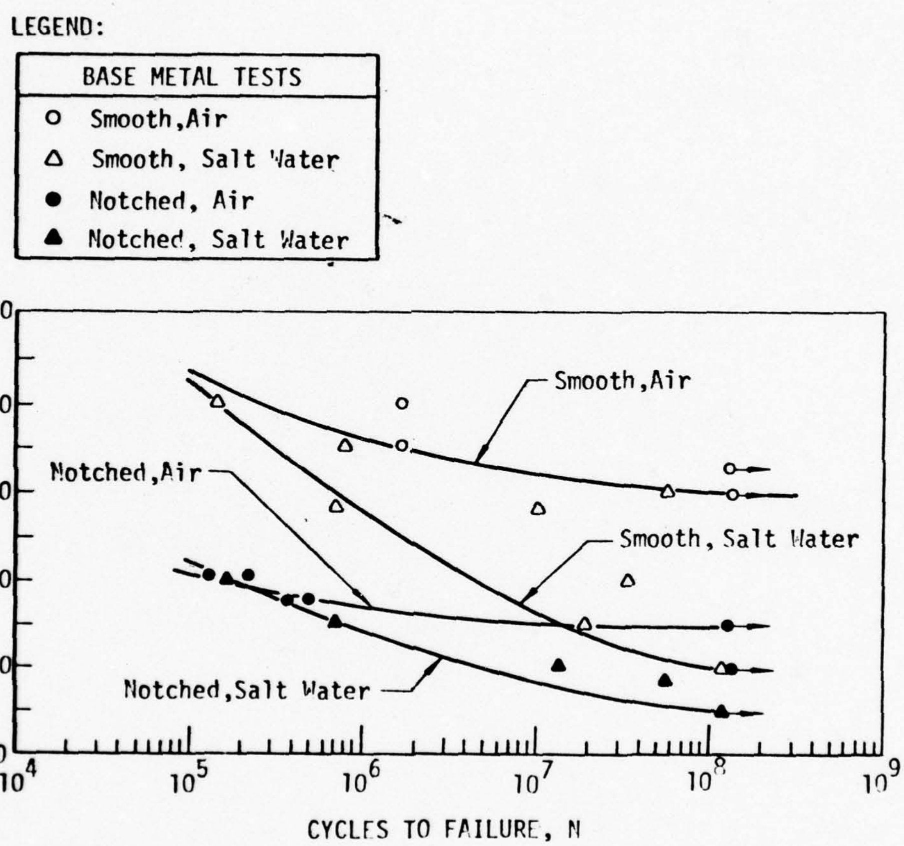


Figure 3: ROTATING CANTILEVER-BEAM FATIGUE STRENGTH OF 17-4 PH STAINLESS STEEL BASE METAL SOLUTION ANNEALED AND AGED AT 1135°F

(Reference 8)

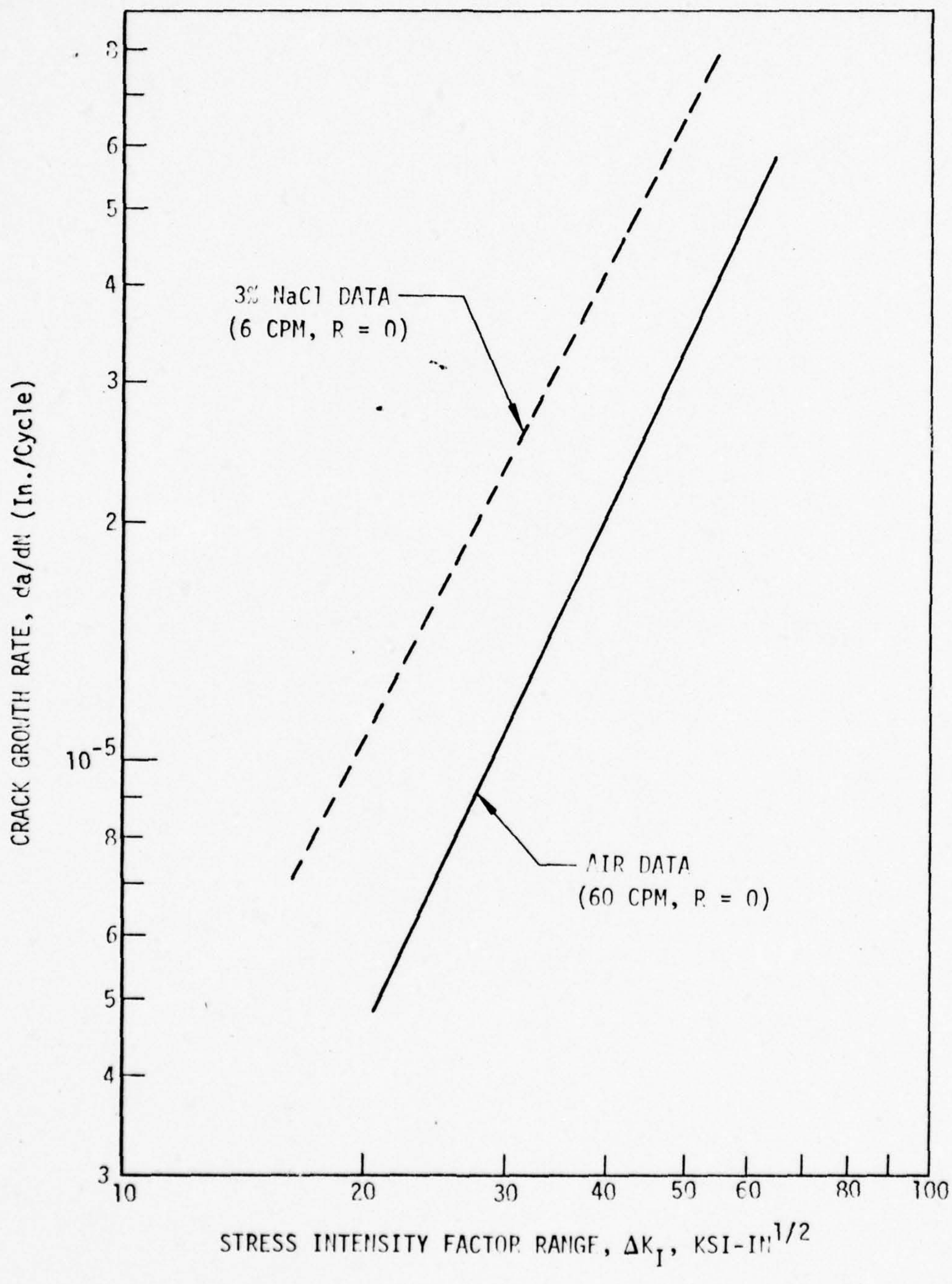


Figure 4: FATIGUE CRACK GROWTH RATES IN AIR AND 3% NaCl BELOW K_{ISCC} FOR HY-130 STEEL
(References 12 & 13)

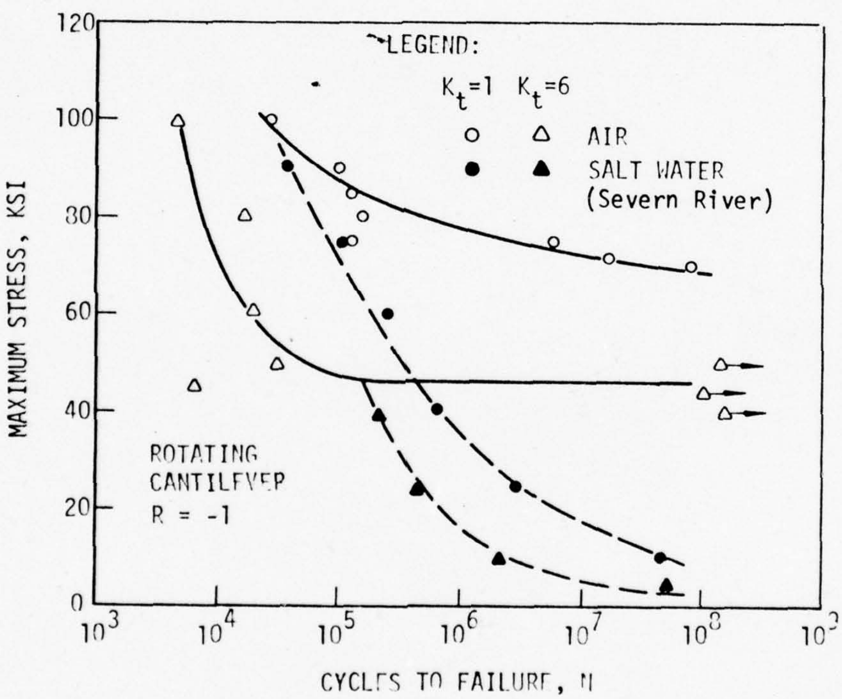


Figure 5: EFFECT OF STRESS CONCENTRATIONS AND BRACKISH RIVER WATER ON FATIGUE STRENGTH OF HY-130 (F_{ty}= 148 Ksi)
Reference 14

NSRDC (17) fatigue test data on Ti 6-2-1-.8 are shown in Figure 6. Both smooth and notched specimens were tested in air and salt water. The tests indicate that salt water has no effect on the fatigue strength of the material.

Experimental Approach

The objectives of the test program are to generate comparative data on the four materials HY 130, 17-4PH, 15-5PH, and Ti 6-2-1-1 and to determine the effects of coatings on the properties of the HY 130.

The current test program, which is still in progress, has been limited to base metal tests. Tabulations of the fatigue and fracture test conditions for each material are presented in Tables 7 and 8 respectively. A positive stress ratio of R = .06 is used for all fatigue tests. This is done to complement the existing fatigue data that were generally performed at a stress ratio of R = -1.0 and to provide a data base for the coating evaluation tests. The program includes parallel tests for 17-4PH and 15-5PH to provide direct comparative data that will determine if any property changes are related to the minor chemistry differences between the two alloys. ASTM substitute ocean water is used for all sea water environment tests (ASTM designation D1141-52).

The following sections describe the test procedures in detail:

Material

Both the 15-5PH and 17-4PH steels were obtained in the form of 1/8" sheet, 1" plate and 2" plate. Originally, HY 130 and Ti 6-2-1-1 were to be obtained in these gages. However, delivery and cost problems made alternate steps necessary. HY 130 was available from within The Boeing Company in the form of sheet and 1.5" plate. It was decided that sufficient data could be obtained using the available material. This did mean that long transverse K_{ISCC} tests had to be eliminated. Ti 6-2-1-.8 was obtained from NRL in the form of 1.0- and 2.0-inch plate. The titanium fatigue specimens were fabricated from the 2-inch plate.

The chemical compositions, heat number and process descriptions are presented (where available) in Table 9.

Since the test program is directed toward hydrofoil applications the materials were tested in the heat treat condition considered most likely to be used in struts and foils. Therefore, the HY 130 was used in the as-received condition as was the Ti 6-2-1-.8 which was in the mill anneal condition. The 15-5PH and 17-4PH steel specimens were fabricated in the solution annealed condition and were subsequently solution annealed and aged at 1050°F by a procedure designed to minimize distortion. This procedure very nearly duplicates the Boeing production heat treat process for 15-5PH and 17-4PH struts and foils.

LEGEND:

		AIR	SALT WATER
SMOOTH	ALTER. BEND	○	●
	ROTAT. CANT.	□	■
NOTCHED	ALTER. BEND	△	▲
	ROTAT. CANT.	◇	◆

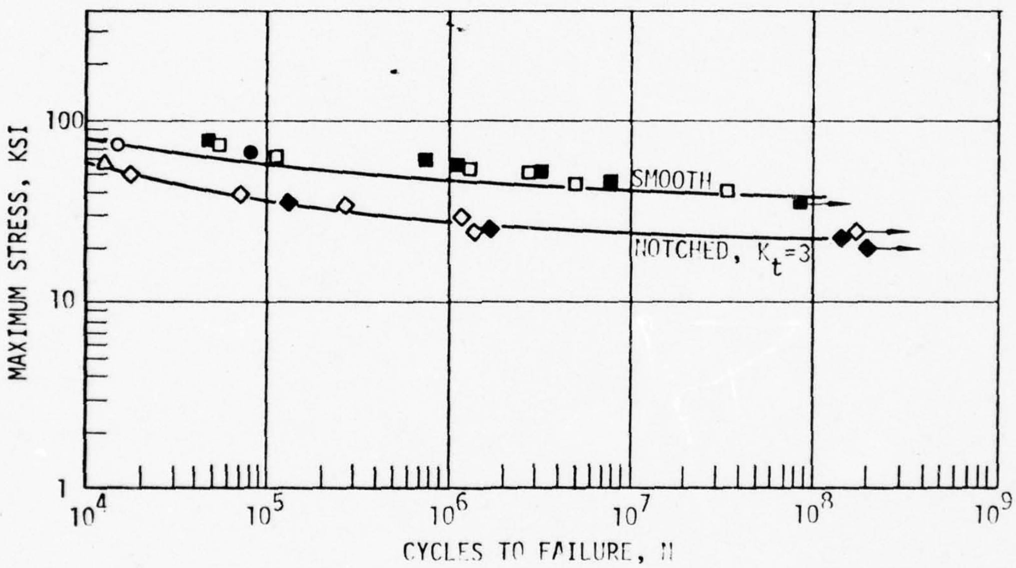


Figure 6: FLEXURAL FATIGUE STRENGTH OF Ti-6Al-2Cb-1Ta-0.8Mo ($F_{ty} \approx 100$ Ksi) (Reference 17)

Table 7: BASE METAL FATIGUE TEST PROGRAM

TEST PARAMETERS (1) / ALLOY	AIR 1800 CPM		ASTM SEA WATER 1800 CPM		ASTM SEA WATER 50 CPM
	SMOOTH	NOTCHED	SMOOTH	NOTCHED	SMOOTH
15-5PH	√	√	√	√	√
17-4PH	√	√	√	√	√
HY-130	√	√	√	√	√
Ti-6-2-1-0.8	√	√	√	√	—

(1) STRESS RATIO, $R = \frac{\sigma_{min}}{\sigma_{max}} = 0.06$ FOR ALL TESTS

Table 8: BASE METAL FRACTURE TEST PROGRAM

	TEST						
	STATIC FRACTURE K_{Ic}	STRESS CORROSION K_{ISCC}			CYCLIC CRACK GROWTH da/dN		
					AIR	ASTM SEA WATER	
		FREELY CORRODING SPECIMEN		SPECIMEN COUPLED WITH 5083-H321		FREELY CORRODING SPECIMEN	SPECIMEN COUPLED WITH 5083-H321
GRAIN ORIENTATION (1)	WR	WR	TR	WR	WR	WR	WR
ALLOY							
15-5PH	✓	✓	✓	✓	✓	✓	✓
17-4PH	✓	✓	✓	✓	✓	✓	✓
HY-130	(2)	(2)	✓	—	✓	✓	✓
Ti-6-2-1-0.8	(2)	(2)	✓	—	✓	✓	✓

(1) WR = LONG TRANSVERSE
TR = SHORT TRANSVERSE
(2) NO TEST: ESTIMATED ASTM THICKNESS REQUIREMENTS ARE IMPRACTICAL

Table 9: CHEMICAL COMPOSITION OF TEST MATERIALS

DESCRIPTION	HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	
HY-130 Steel													
1.50" Plate (MIL-S-24371)	USS 5P5608	0.12	0.74	0.005	0.006	0.24	0.07	4.97	0.56	0.48	0.07	0.01	
3/16" Sheet	N/A							5.00	0.38	0.49	0.058		
17-4PH Steel Boeing BMS 7-84 Consumable Electrode Vacuum Melt													
2.0" Plate	Republic 3821541	0.04	0.36	0.028	0.004	0.58	3.32	5.00	15.92				Ta+Cb=0.35
1.0" Plate / 1/8" Sheet	3811539	0.046	0.35	0.027	0.004	0.50	3.12	4.92	15.80				Ta+Cb=0.32
15-5PH Steel AMS-5659B Chem AMS-5604 Phys Consumable Electrode Vacuum Melt													
2.0" Plate	Republic 3821329	0.038	0.36	0.026	0.003	0.43	3.29	4.86	14.99				Ta+Cb=0.31
1.0" Plate	3821832	0.035	0.37	0.029	0.004	0.42	3.34	4.88	15.00				Ta+Cb=0.31
1/8" Sheet	3811583	0.038	0.33	0.029	0.004	0.48	3.26	4.69	15.15				Ta+Cb=0.31
Ti-6-2-1-0.8		C	N	Fe	Al	Cb	Ta	Mo	O	H (ppm)			
2.0" Plate	RMI 29321	0.02	0.007	0.07	6.1	2.1	1.1	0.70	0.068	59			
1.0" Plate	292555	0.02	0.007	0.06	6.1	2.3	1.0	0.73	0.073	36 to 79			

Tensile Tests

The tensile specimens used, shown in Figure 7, were machined from each sheet and plate used in the program and tested. For 15-5PH and 17-4PH steel, where heat treatment was required before test, the tensile specimens were heat treated with the fatigue or fracture specimens.

Fatigue Tests

All fatigue tests were conducted with the smooth and notched uniaxial fatigue specimens shown in Figure 8.

The general procedure for fabrication of the fatigue specimens was to cut out specimen blanks, slab mill the faces (target surface finish 30 micro-inches RMS) complete all machining operations and debur all edges. This was followed by dye penetration inspection and hand rework as required. At this point the HY 130 and Ti 6-2-1-.8 were ready for test. The 15-5PH and 17-4PH steel specimens were machined in the solution treated condition and then solution heat treated and age hardened to the H-1050 condition before test.

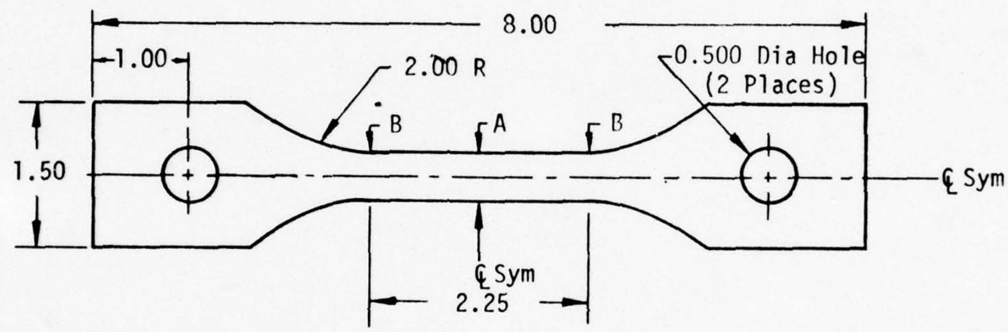
The PH specimens were coated with Turco(R) pretreat before heat treatment to prevent oxidation, but some pitting was observed in the center holes of the notched specimens. Therefore, all center holes had to be reamed from the standard .1875" diameter to .199" after heat treatment. This increased the gross area stress concentration factor, k_t, from 3.13 to 3.15.

All fatigue tests have been conducted at The Boeing Commercial Airplane Company Structures Laboratory. Specimens were tested at 1800 cpm in Baldwin SF-10U universal fatigue machines and at 50 cpm with a Boeing-made mechanical fatigue machine. The tests were conducted at room temperature with a stress ratio $R = .06$. Failure was defined as complete fracture of the specimens.

The corrosion fatigue test setup is shown in Figure 9. The specimen is wetted by ASTM sea water contained in a plastic bag which encloses the test section. A specimen under test in salt water is shown in Figure 10. The sea water is circulated by means of the plumbing system sketch in Figure 11. This plumbing system keeps the sea water well aerated and is all plastic to protect against galvanic corrosion.

Fracture Tests

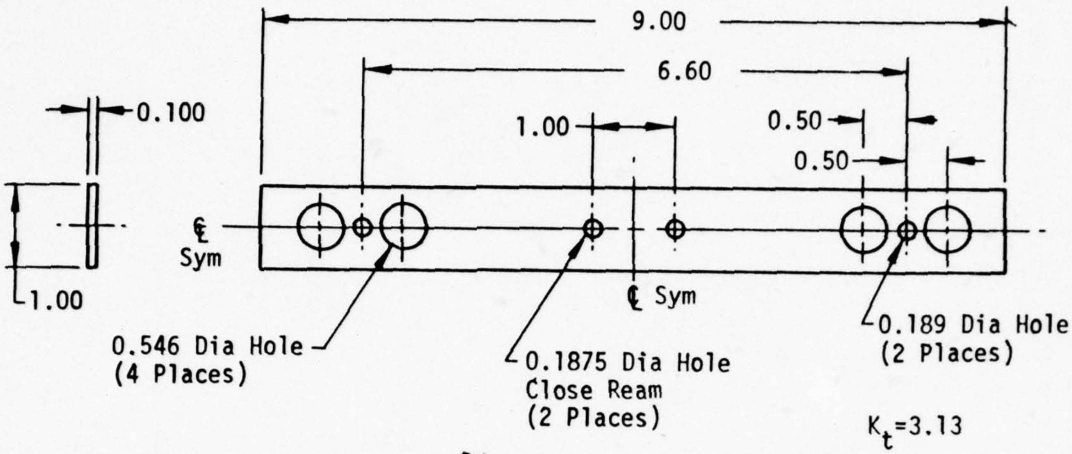
The fracture specimens used in this program are shown in Figures 12 through 15. All are wedge open load (WOL) type specimens. The general fabrication procedures were similar to those for the fatigue specimens except that the surface finish was not carefully controlled on the fracture specimens.



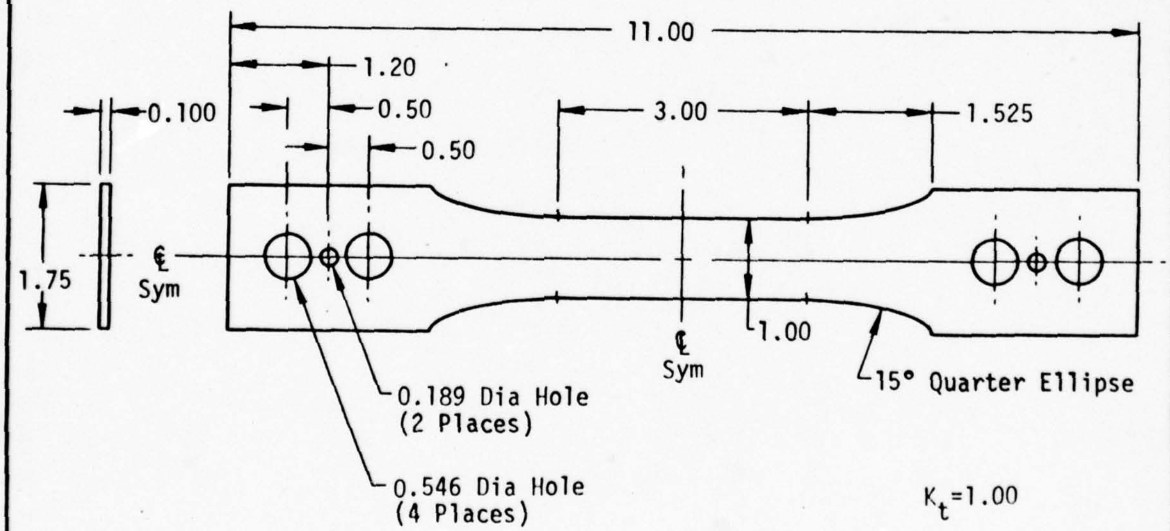
A	0.50 ± 0.005
B	A $^{+0.003}_{-0.005}$

All Tolerances ± 0.05 Except As Noted

Figure 7: TENSILE SPECIMEN



NOTCHED FATIGUE SPECIMEN



SMOOTH FATIGUE SPECIMEN

Figure 8: FATIGUE SPECIMENS

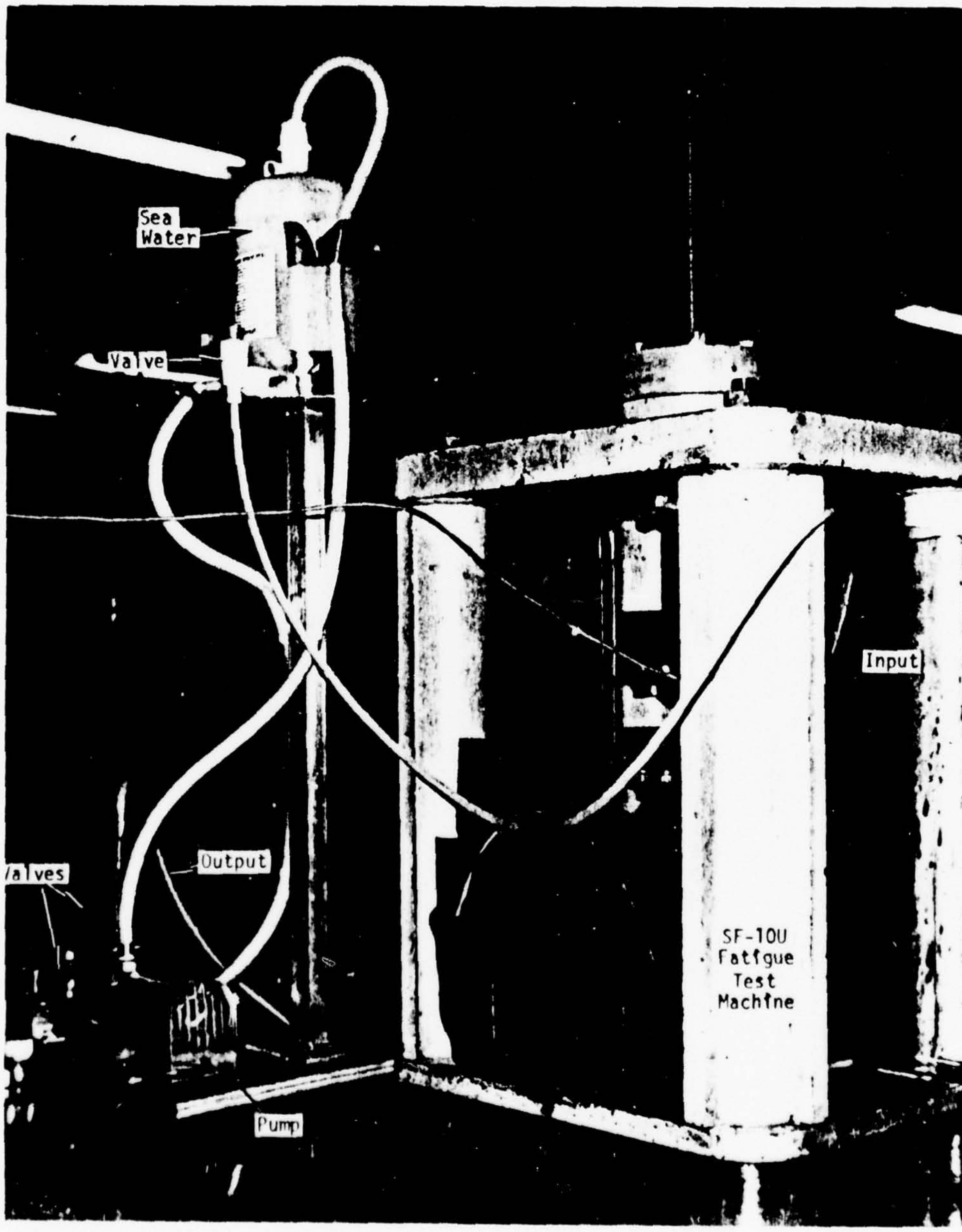


Figure 9: CORROSION FATIGUE TEST SETUP

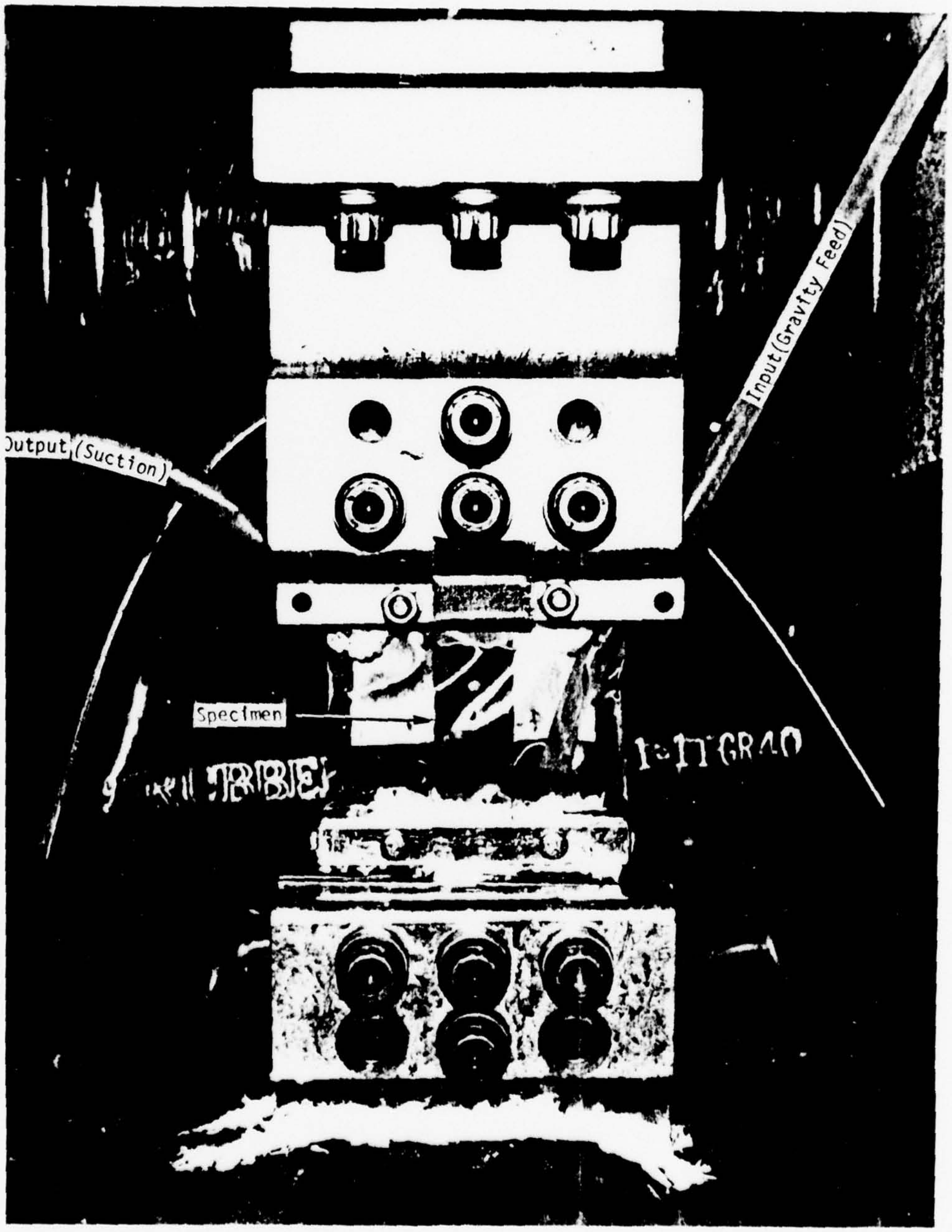


Figure 10: CLOSE UP OF NOTCHED SPECIMEN CORROSION FATIGUE TEST SHOWING PLASTIC BAG ENVIRONMENT CHAMBER

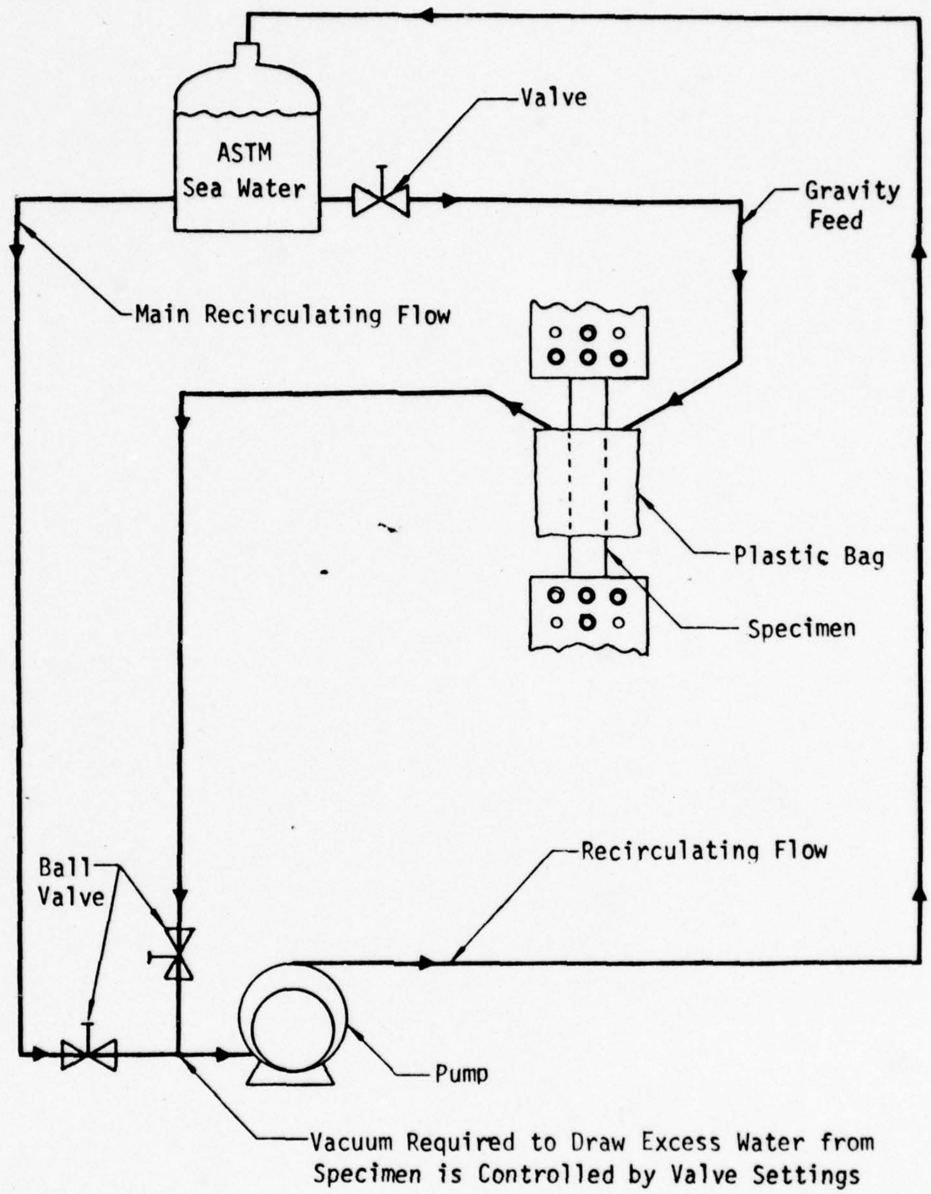


Figure 11: SCHEMATIC OF CORROSION FATIGUE TEST PLUMBING SETUP

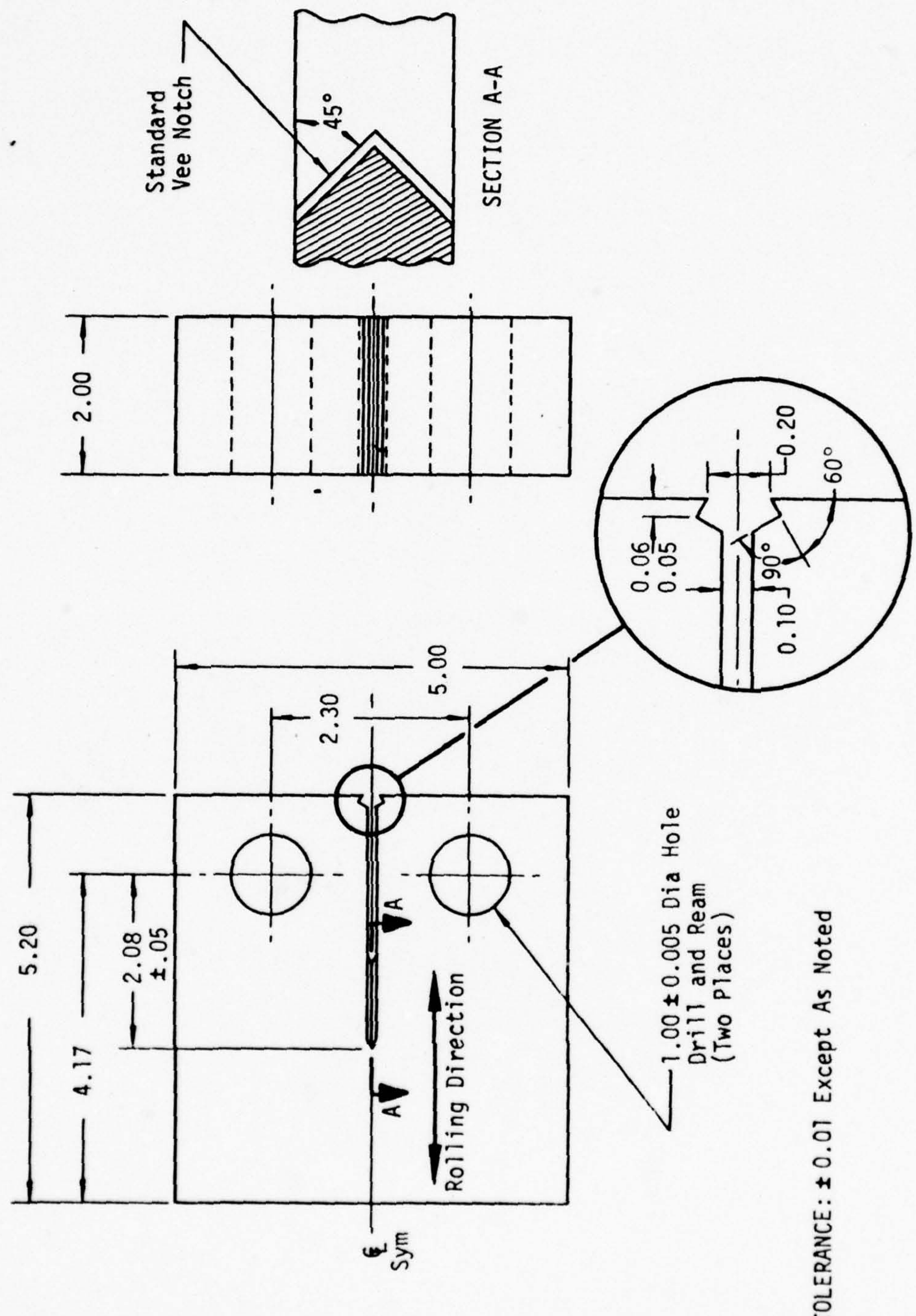


Figure 12: COMPACT TENSION SPECIMEN

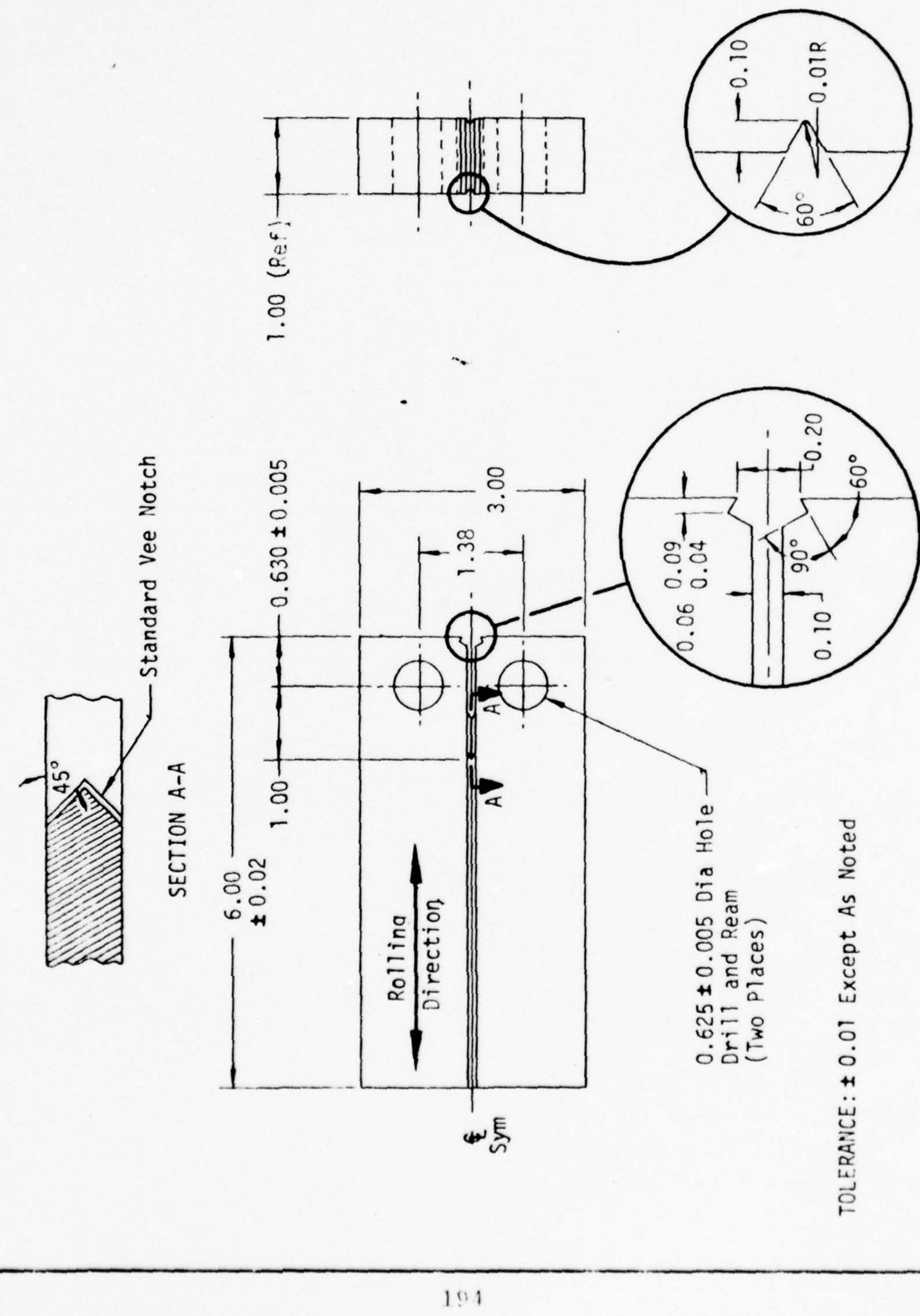


Figure 13: CYCLIC GROWTH DCB SPECIMEN

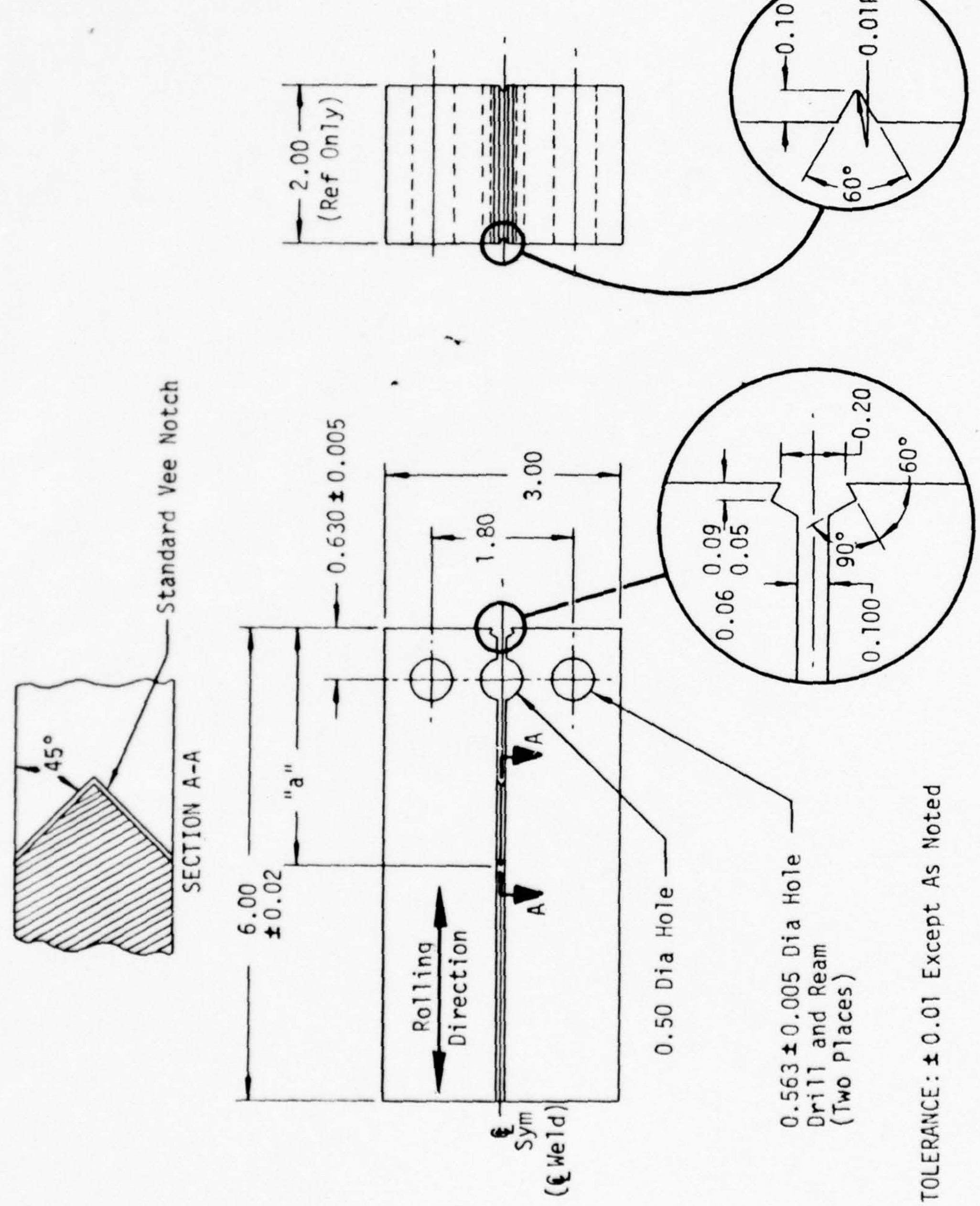


Figure 14: WR-SCC DCB SPECIMEN

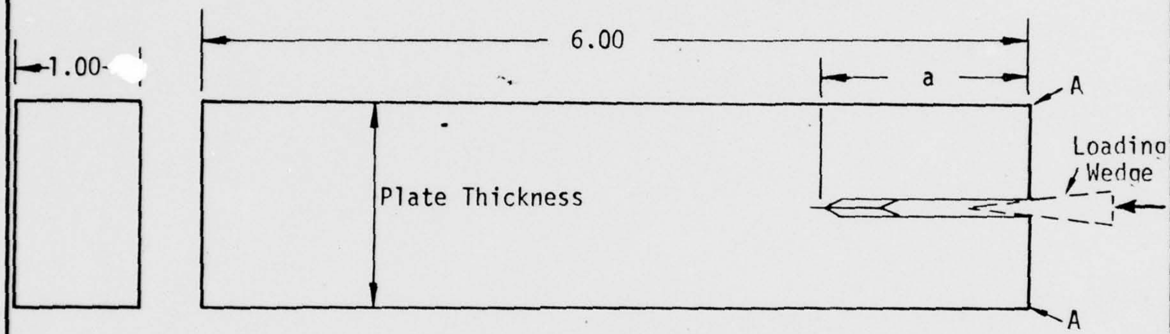


Figure 15: TR-SCC DCB SPECIMEN

Crack starters on all specimens consist of a .10 inch wide milled slot terminating in a chevron "Vee" notch. When required, fatigue precracking was accomplished in accordance with ASTM (E 399-70T) recommended procedures.

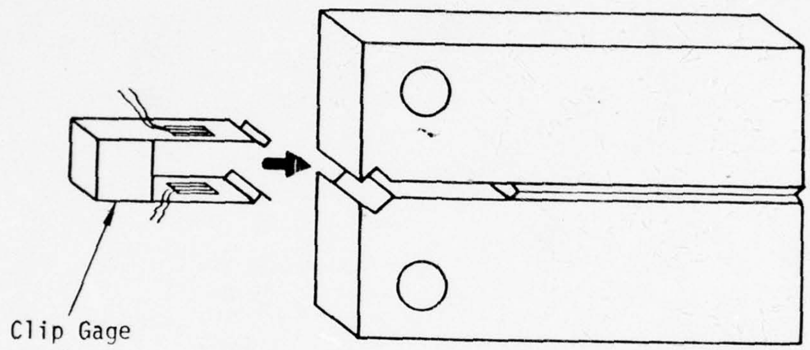
Plane strain fracture toughness tests were conducted with the compact tension (CT) specimen shown in Figure 12. The specimens were designed and tested in compliance with ASTM (E 399-70T) recommended procedures.

Modified forms of the compact tension specimens were used for the stress corrosion cracking (K_{ISCC}) and cyclic flaw growth tests. The modification consists of extending the back side of the CT specimen to increase the crack growth capacity. This type of specimen is referred to as a Double Cantilever beam (DCB) specimen.

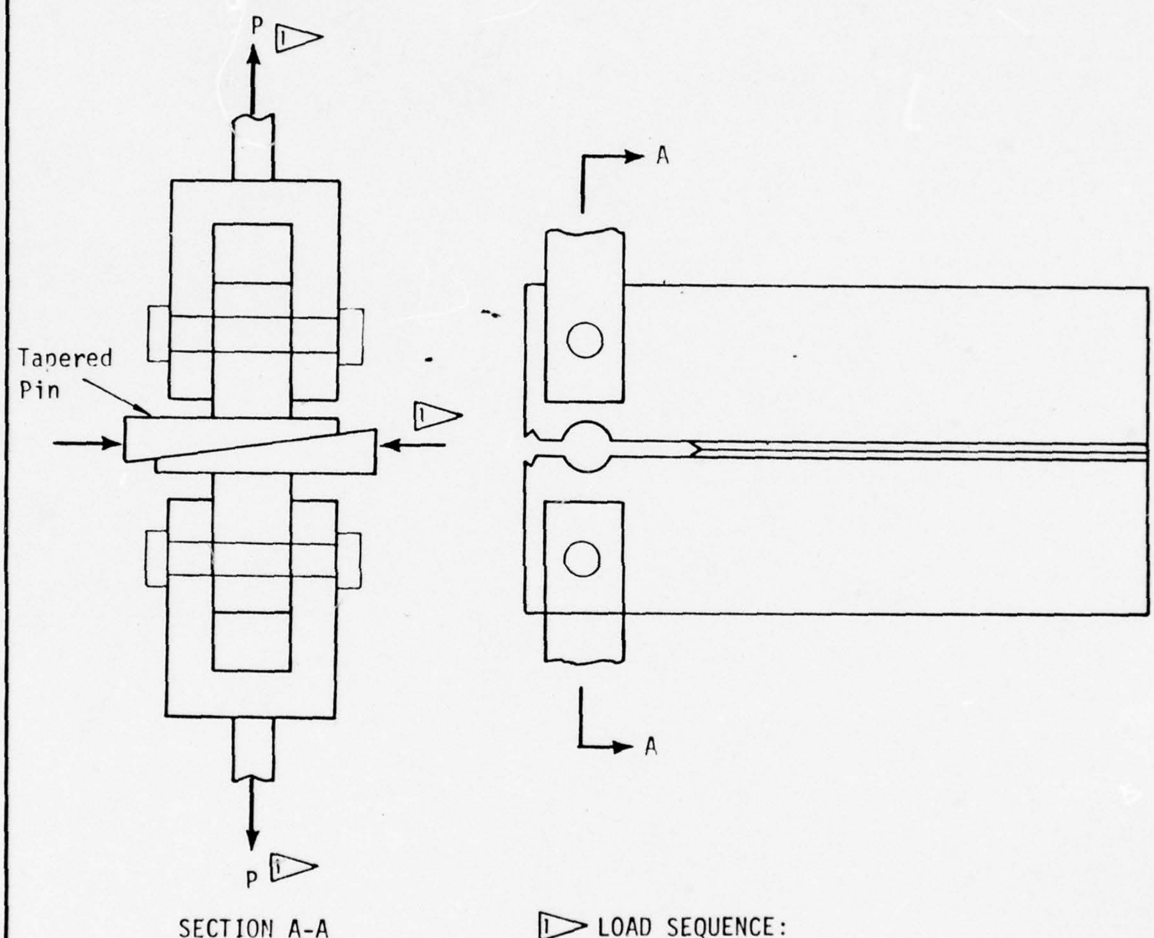
The cyclic flaw growth DCB specimen used for all alloys is shown in Figure 13. These specimens have a long transverse (WR) grain orientation. The specimens were side grooved to prevent the crack from rotating from the original crack plane. Loads were applied at the holes provided in the specimen. The cyclic tests were conducted by using a set of progressively higher fatigue loads to grow cracks over a series of crack length increments. Air cyclic fatigue loads were applied at a rate of 50 cpm while for corrosion fatigue loads were applied at a rate of 6 cpm. A stress ratio of R = .05 was used for all tests. All crack growth specimens were instrumented with NASA clip gages to obtain readings of opening mode displacement as illustrated in Figure 16.

A crack opening displacement vs cycles record was made during the test. This data can be reduced to stress intensity vs cyclic growth rate data (see the following section, "Analysis of Fracture Data" for details).

Long transverse (WR) and short transverse (TR) SCC specimens are displayed in Figures 14 and 15, respectively. In these specimens, the stress intensity, K_I, decreases with increasing crack length under constant deflection conditions. This affords the opportunity to observe rates of growth at K_I levels over which growth takes place and K_{ISCC} levels at which crack growth stops. The constant deflection condition is achieved in two ways. For the WR specimen, tapered pin loading is used in conjunction with an initial applied load as shown in Figure 17. The procedure involves deflecting the specimen jaws by loading the specimen and then driving in the tapered pins from each side of the specimen. The deflection is measured with a NASA type clip gage. For the TR specimens, the wedge is driven into the jaws of the specimen as illustrated in Figure 15. The deflection of the jaws is measured with a micrometer at the points noted by an "A" in the illustration.



Fiaure 16: DCB SPECIMEN INSTRUMENTATION



1 LOAD SEQUENCE:

(1) Load P Is Applied To Achieve 90% Of Required Stress Intensity

(2) Load P Is Held Constant And The Tapered Pins Are Pressed Togeather To Achieve The Required Crack Opening Displacement

Figure 17: LOADING METHOD FOR WR-SCC SPECIMENS

The SCC tests are conducted by wetting the crack tip in ASTM sea water and loading the specimens, as described above, to a K level above the anticipated K_{ISCC}. The specimens are then placed in a sealed glass container filled with ASTM sea water. Periodic crack readings are taken by removing the specimen from the jar using white glove techniques.

Analysis of Fracture Data

Static fracture toughness values are calculated from CT specimen results using ASTM recommended procedures (E 399-70 T). Stress intensities for pin loaded DCB specimens are calculated using the following equation:

$$K_I = \frac{2p}{b}\left(\frac{b}{b_n}\right)^{1/2}\left[\frac{3\ (a + 0.6h)^2 + h^2}{(1 - \nu^2)\ h^3}\right]^{1/2} \tag{1}$$

where p is applied load

b is specimen width

b_n is crack width

h is one-half the specimen height

E is Young's modulus

a is crack length

ν is Poisson's ratio

Crack growth rates for corrosion fatigue tests are determined using crack displacement versus cycles records. Crack displacement measured at predetermined cyclic intervals and corresponding compliance values are determined by dividing the measured displacements by the applied load. Crack lengths corresponding to the individual compliance values are determined from the first air crack growth specimen for each alloy. Increments of crack length are divided by the corresponding number of loading cycles to determine average crack growth rates over the cyclic intervals. Stress intensity factors at the beginning and end of each cyclic interval are averaged to determine the stress intensity factor against which average crack growth rates are plotted. Stress intensity factors are calculated using Equation 1.

For stress corrosion cracking results the stress intensity factors are determined by measuring the crack deflection (δ) and substituting the corresponding measured value of a into the equation

$$K_I = \frac{\delta\, Eh \left[3h\,(a + 0.6h)^2 + h^3 \right]^{1/2}}{\sqrt{(1 - \nu^2)}\; 4 \left[(a + 0.6h)^3 + h^2\, a \right]} \left(\frac{b}{b_n} \right)^{1/2} \qquad (2)$$

where the symbols represent the same measurements as in Equation 1.

Results

Tensile Tests

The tensile tests results are presented in Table 10.

Fatigue Tests

Base metal fatigue tests at 1800 cpm have been completed for HY 130, 15-5PH and 17-4PH and the results are plotted in Figures 18, 19 and 20, respectively. Fatigue tests of Ti 6-2-1-.8 have not been completed but the results to date are plotted in Figure 21.

Four smooth specimens have been tested in sea water at 50 cpm. This includes two 15-5PH specimens and one each of the HY 130 and 17-4PH steel specimens. The results are plotted in Figure 22 along with the corresponding S-N curves from the 1800 cpm fatigue tests.

Fracture Tests

The original static fracture tests were to be conducted with just the CT type specimen. However, a long transverse DCB specimen from each PH steel was used for K_{IC} testing. Also, it was possible to estimate the short transverse fracture toughness of both PH steels because of the behavior of the short transverse DCB specimen during wedge loading. The crack starter slot was not precracked prior to wedge loading and when the wedges were forced into the starter slot a sharp crack would initiate and extend into the specimen by a series of discrete bursts of growth. Thus, by recording the crack opening displacement versus crack lengths, the necessary data was generated to compute the short transverse fracture toughness. A summary of static fracture properties developed for 15-5PH and 17-4PH are presented in Table 11.

Cyclic flaw growth tests have been conducted in air and under freely corroding conditions in sea water on all four materials. Cyclic stress intensity versus crack growth rate data for HY 130 in the two environments are plotted in Figure 23. Air and sea water crack growth rate data for the PH steels are plotted in Figures 24 and 25 and the cyclic growth behavior of Ti 6-2-1-.8 is shown in Figure 26.

A compilation of stress corrosion cracking test results is presented in Table 12.

Table 10: MECHANICAL PROPERTIES

MATERIAL	GRAIN ORIENTATION	TEST TEMPERATURE	ULTIMATE (1) STRENGTH (KSI)	YIELD (1) STRENGTH (KSI)	ELONGATION (1) (% IN 2.0")	REDUCTION (1) IN AREA (%)
HY-130 SHEET	L	ROOM TEMPERATURE	150.5	144.0	14	57
	T		150.7	142.0	14	53
HY-130 PLATE	L		156.1	146.9	17	63
	T		156.8	148.6	17	65
17-4PH SHEET (H1050)	L		164.0	158.6	13	45
	T		163.6	158.6	13	47
15-5PH SHEET (H1050)	L		170.4	165.0	11	67
	T		167.8	162.4	11	61
15-5PH 2.0" PLATE (H1050)	L		179.1	170.5	13	37
	T		177.0	170.1	14	40
15-5PH 1.0" PLATE (H1050)	L		170.9	165.4	16	59
	T		171.6	166.9	15	57
17-4PH 2.0" PLATE (H1050)	L		170.3	161.5	16	61
	T		171.9	162.6	16	57
17-4PH 1.0" PLATE (H1050)	L		165.5	158.4	19	61
	T		166.0	157.5	19	59
Ti-6-2-1-1 2.0" PLATE	L		122.2	111.1	15	40
	T		124.2	115.3	15	37
Ti-6-2-1-1 1.0" PLATE	L		118.8	103.6	13	33
	T		121.5	108.5	13	31

(1) AVERAGE OF TWO TESTS

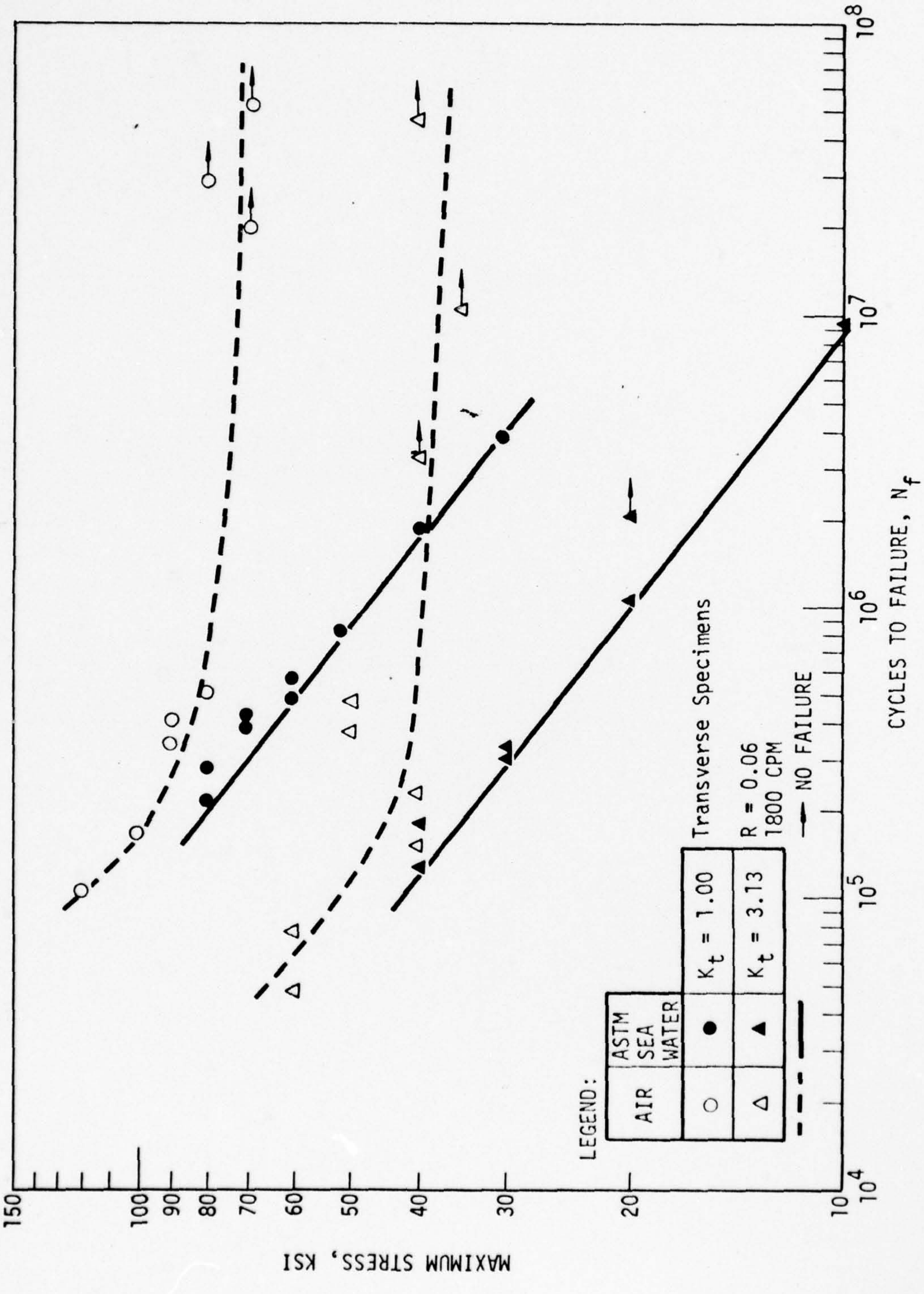


Figure 18: HY-130 STEEL FATIGUE STRENGTH IN AIR AND SEA WATER

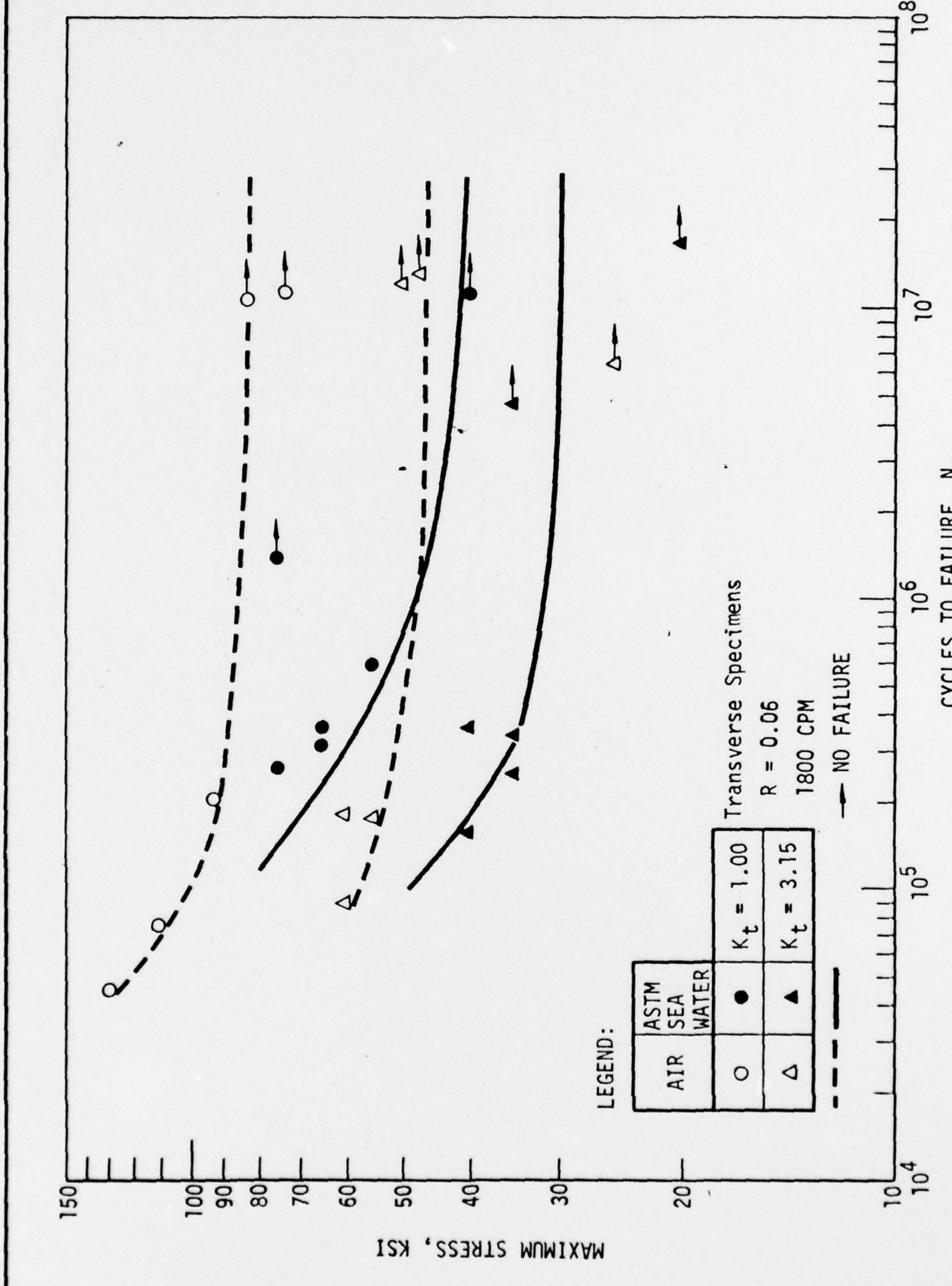


Figure 19: 15-5PH STEEL FATIGUE STRENGTH IN AIR AND SEA WATER

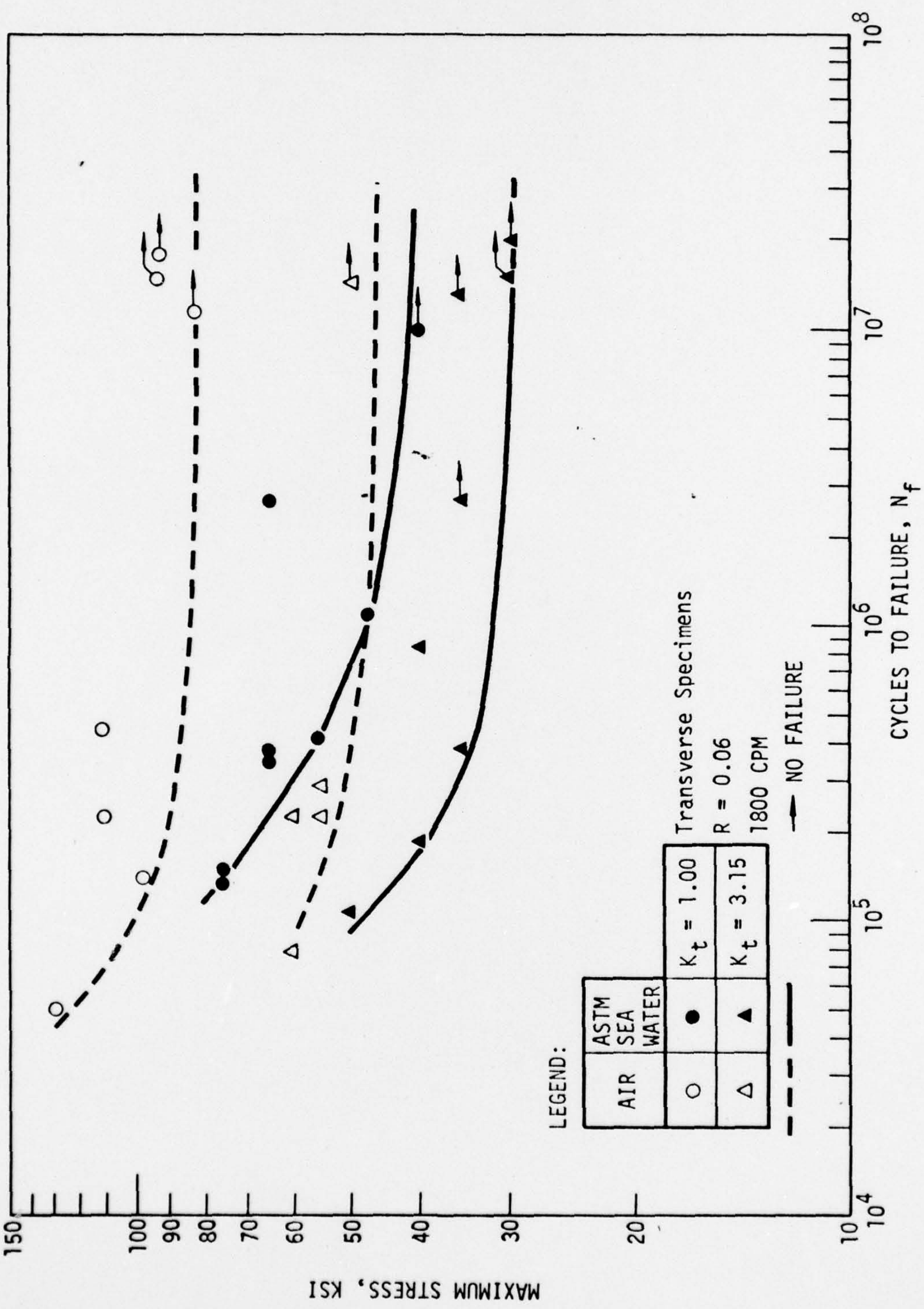


Figure 20: 17-4PH STEEL FATIGUE STRENGTH IN AIR AND SEA WATER

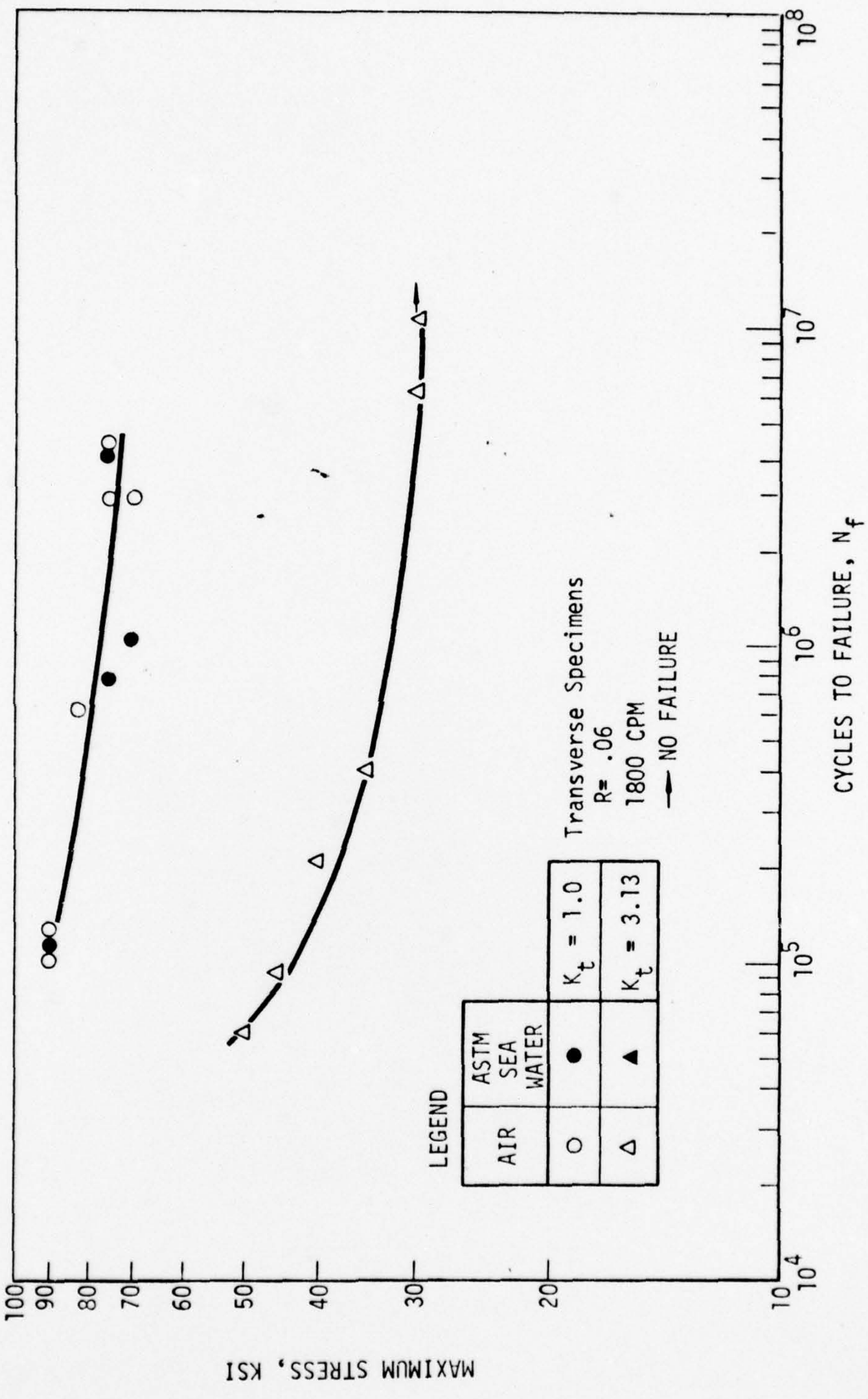


Figure 21: Ti-6-2-1-.8 FATIGUE STRENGTH IN AIR AND SEA WATER

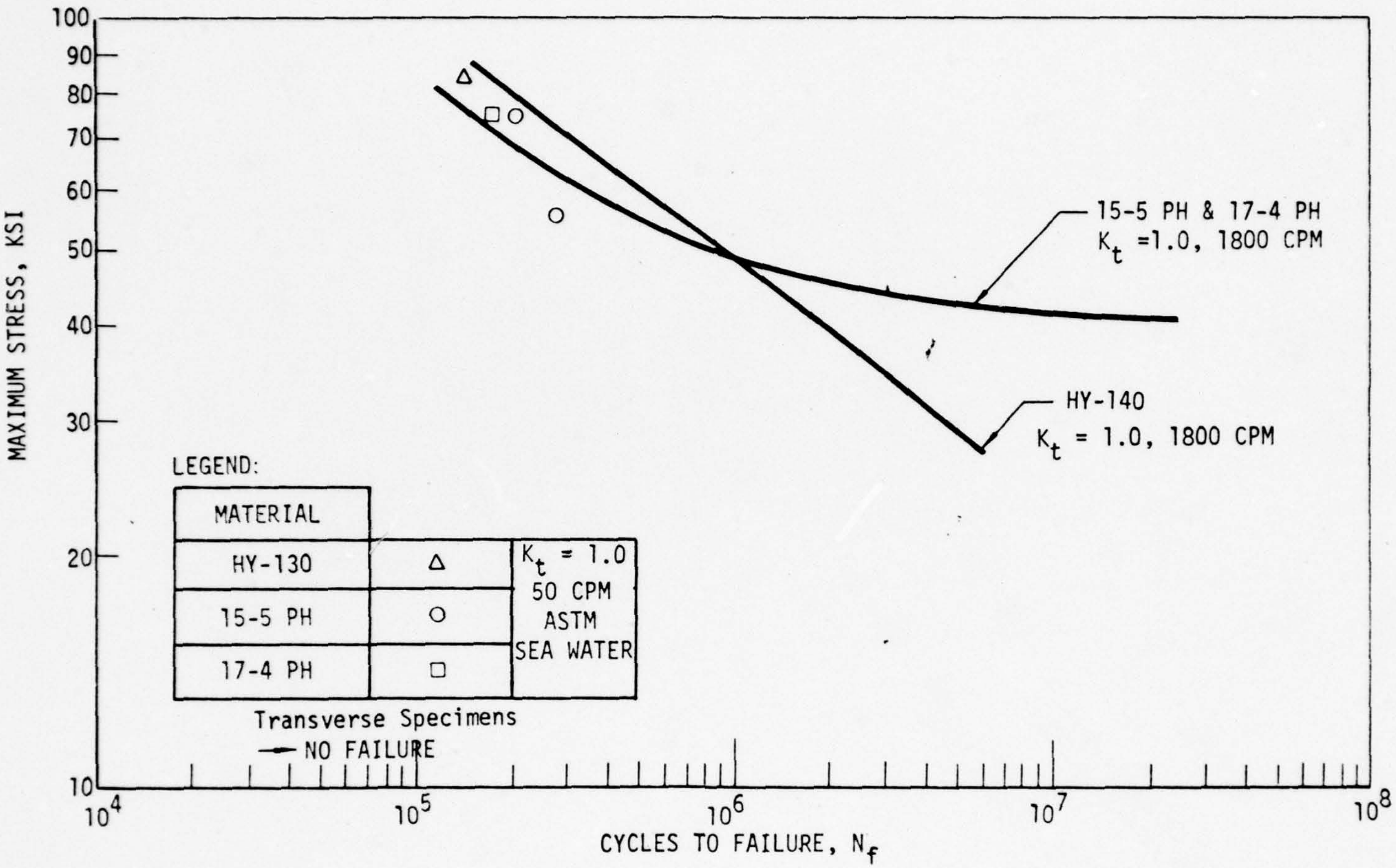


Figure 22; EFFECT OF FREQUENCY ON CORROSION FATIGUE STRENGTH OF HY-130, 15-5 PH AND 17-4 PH

Table 11: STATIC FRACTURE TEST RESULTS

ALLOY	GRAIN ORIENTATION	SPECIMEN TYPE	K_{Ic} (Ksi-In$^{1/2}$)	REMARKS
15-5PH (H1050)	WR	CT (Figure 12)	92.5	Average Of Two Tests
17-4PH (H1050)	WR	CT (Figure 12)	95.5	Average Of Two Tests
15-5PH (H1050)	WR	3"x6"x2" DCB (Figure 14)	112.5	One Test
17-4PH (H1050)	WR	3"x6"x2" DCB (Figure 14)	105.0	One Test
15-5PH (H1050)	TR	2"x6"x1" DCB (Figure 15)	100.0 ± 10	Approximate K_{Ic} Based On Wedge Loading Before TR-SCC Test
17-4PH (H1050)	TR	2"x6"x1" DCB (Figure 15)	52.5 ± 5.2	Approximate K_{Ic} Based On Wedge Loading Before TR-SCC Test

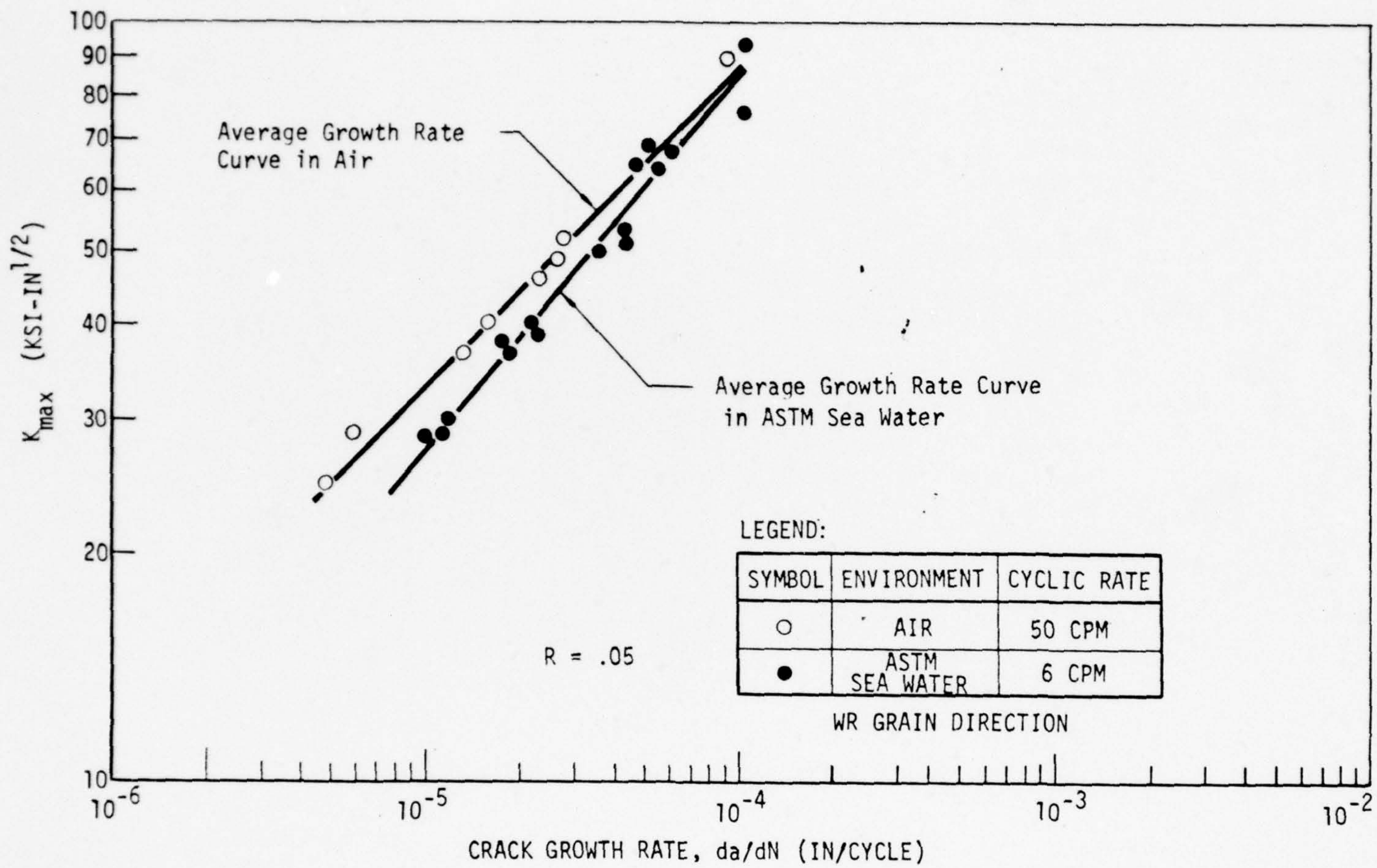


Figure 23: CRACK GROWTH RATE OF HY-130 IN AIR AND ASTM SEA WATER

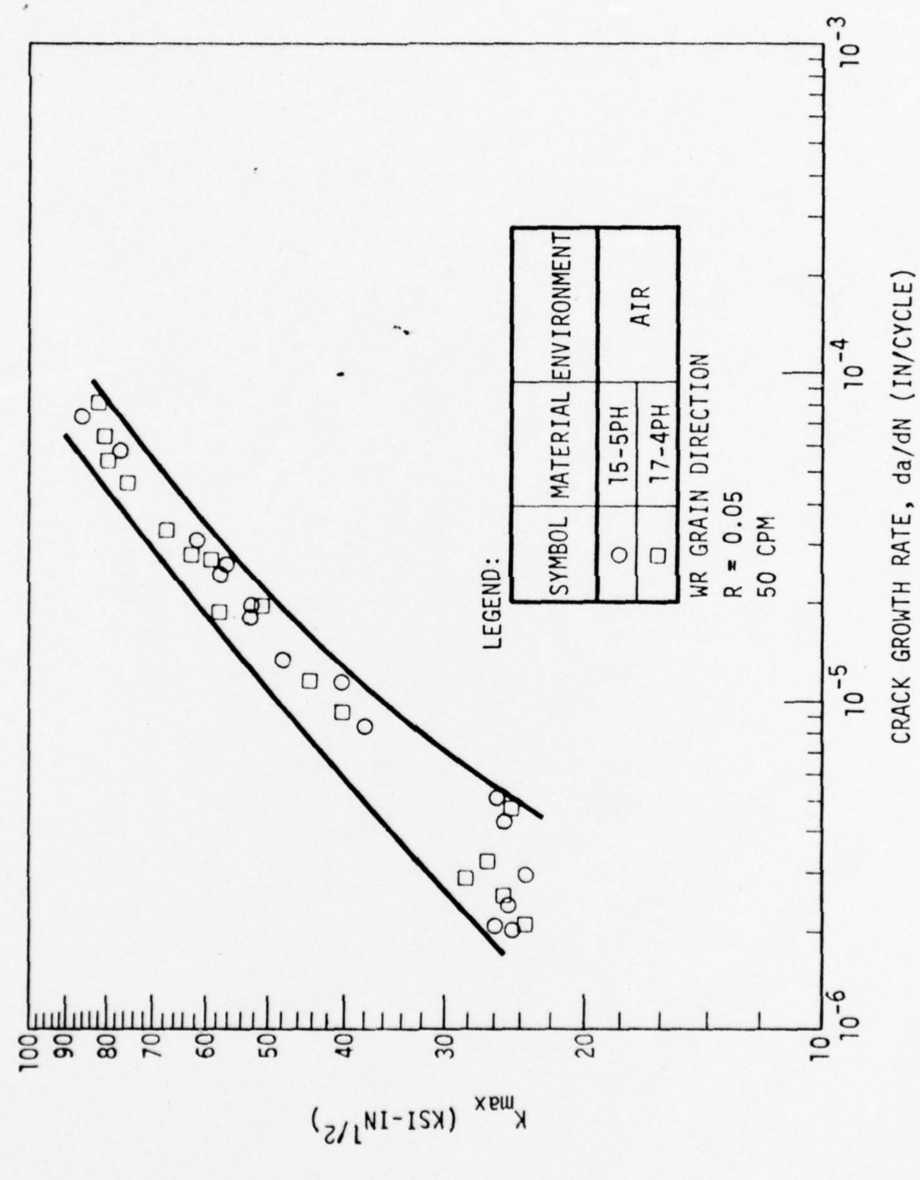


Figure 24: CRACK GROWTH RATE OF 15-5PH AND 17-4PH IN AIR

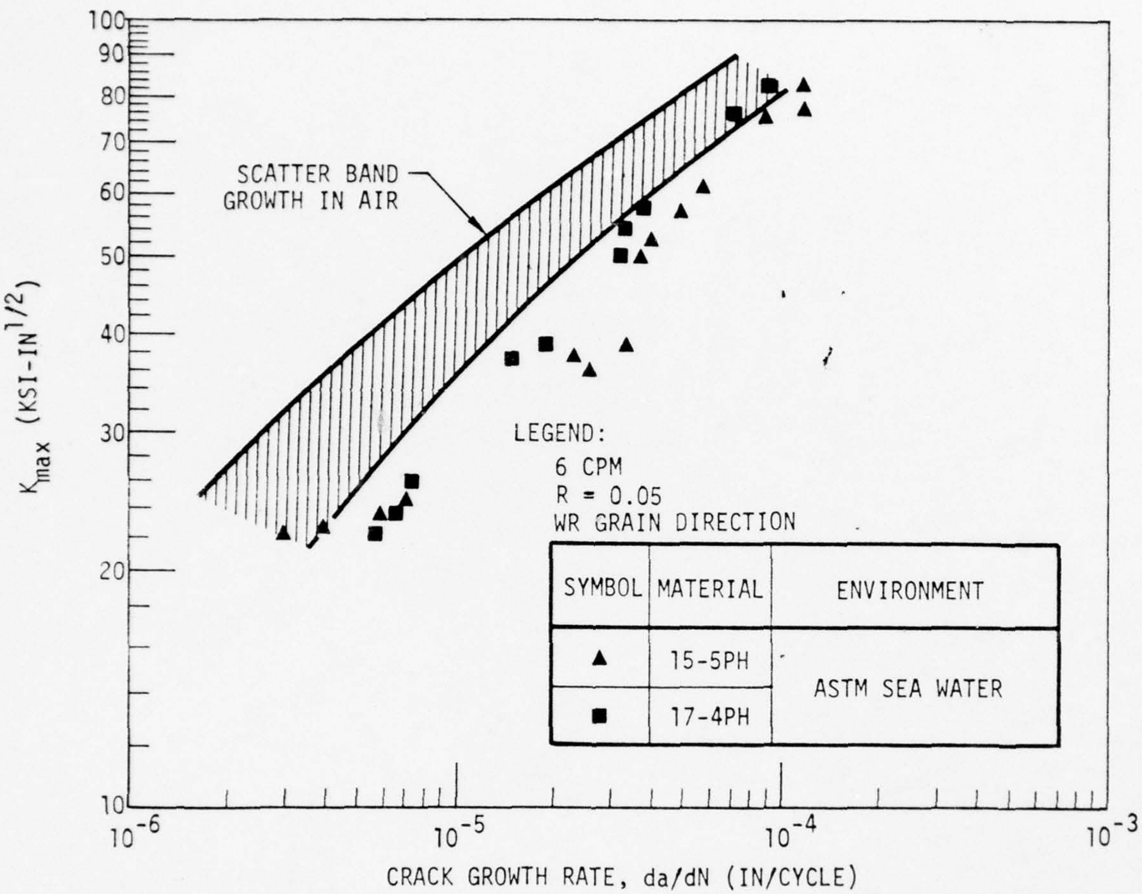


Figure 25: CRACK GROWTH RATE OF 15-5PH AND 17-4PH IN ASTM SEA WATER

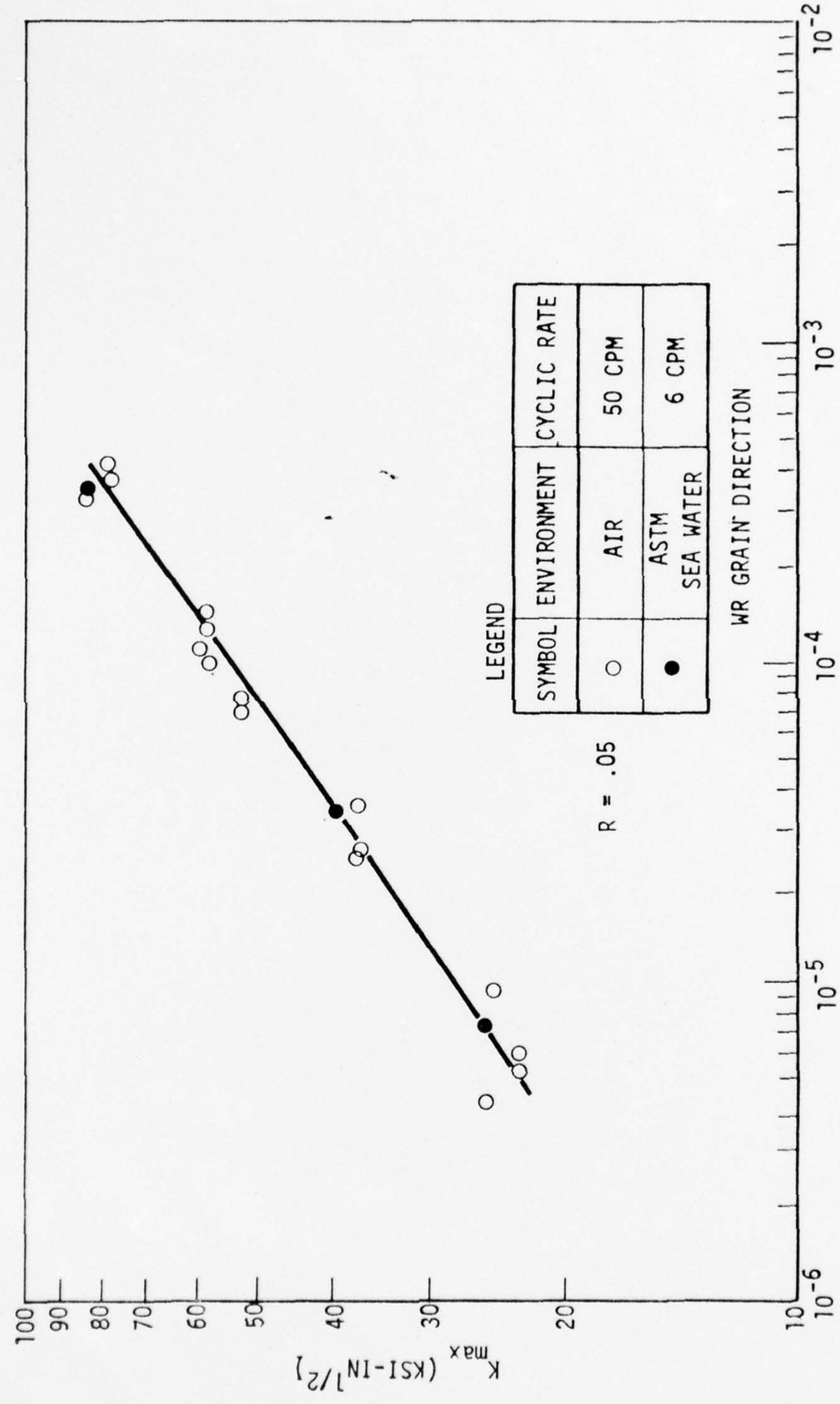


Figure 26: CRACK GROWTH RATE OF Ti 6-2-1-.8 IN AIR AND ASTM SEA WATER

Table 12: K_{ISCC} TEST RESULTS

ALLOY	SPECIMEN NUMBER	GRAIN ORIENTATION	ENVIRONMENT: ASTM SEA WATER		TEST DURATION (Hours)	INITIAL K_I (Ksi $\sqrt{In}$)	GROWTH (Inch)	FINAL K_I (Ksi $\sqrt{In}$)	K_{ISCC} (Ksi $\sqrt{In}$)
			FREELY CORRODING	COUPLED WITH 5083-H321					
15-5PH (H1050)	5WR-1	WR	√		1000	84	NO GROWTH	84	> 84
	5WR-2	WR		√	1000	84	POSSIBLE TRACE	84	> 84
	5WR-4	WR	√			102	TEST IN PROGRESS		
	5-TR-1	TR	√		1000	~ 75	NO GROWTH	~ 75	> 75
	5-TR-2	TR	√		1000	~100	NO GROWTH	~100	>100
17-4PH (H1050)	4WR-1	WR	√		1000	84	NO GROWTH	84	> 84
	4WR-2	WR		√	1000	84	NO GROWTH	84	> 84
	4WR-4	WR	√			95	TEST IN PROGRESS		
	4-TR-1	TR	√		1000	~ 40	NO GROWTH	~ 40	> 40
	4-TR-2	TR	√		1000	~ 52.5	NO GROWTH	~ 52.5	> 52.5
HY-130	HY-TR-1	TR	√		1000	80	NO GROWTH	80	> 80
	HY-TR-2	TR	√		1000	80	NO GROWTH	80	> 80
Ti 6-2-1-0.8	Ti-TR-1	TR	√		500	70	0.60	(1)	
	Ti-TR-2	TR	√		500	70			

(1) TEST JUST COMPLETED AND RESULTS ARE UNDER INVESTIGATION

Discussion of Results

The fatigue strength of HY 130 is severely reduced by salt water when cycled at a stress ratio R = .06. As shown in Figure 18, salt water reduced the fatigue strength at 10^7 cycles from 80 ksi to approximately 25 ksi for smooth specimens and from 40 ksi to 10 ksi for notched specimens. This material behaved predictably under corrosion fatigue conditions and it appears that meaningful coating evaluation tests can be conducted with a minimum number of specimens. There does not seem to be a frequency effect for corrosion fatigue based on the one HY 130 test shown in Figure 22.

The air and corrosion fatigue strengths of 15-5PH are nearly identical to the corresponding fatigue strengths of 17-4PH. So nearly identical that the same set of S-N curves fit the fatigue data for both alloys (see Figures 19 and 20). When compared to HY 130, the PH steels have higher fatigue strengths but the scatter in the PH steel data is also larger. Salt water reduced the fatigue strength at 10^7 cycles from 90 ksi to 40 ksi for smooth specimens and from 45 ksi to 30 ksi for notched specimens of the 15-5PH and 17-4PH. No definite frequency effect can be deduced from the 50 cpm fatigue test data.

The Ti 6-2-1-.8 fatigue tests are still in progress so it is difficult to draw any meaningful conclusions as yet. However, it does appear that salt water has little if any effect on the fatigue strength of this alloy. This is in agreement with the NSRDC data displayed in Figure 6.

The static fracture test results presented in Table 11 provide an excellent comparison between 15-5PH and 17-4PH. The long transverse (WR) results are similar for the two alloys. The CT test results show slightly higher toughness for 17-4PH while the opposite is true for the DCB test results. The most significant difference between the two PH alloys was determined by the short transverse (TR) fracture tests. As shown in Table 11, the short transverse fracture toughness of 17-4PH is half that for 15-5PH.

The stress corrosion cracking test results listed in Table 12 show that 15-5PH (H 1050) and 17-4PH (H 1050) are highly resistant to stress corrosion cracking in sea water. No growth has been detected in any specimens. This includes WR and TR specimens in a freely corroding environment and WR specimens coupled to 5083-H321 (aluminum). Since no growth was detected in these specimens after 1000 hours, two specimens were used for static fracture tests. They indicated higher K_{IC} values than were obtained from the CT specimens. This allowed loading two specimens to higher stress intensities without risk of failure. These two specimens are in test at this time and no growth has been detected after approximately 750 hours.

No stress corrosion cracking was detected in the short transverse HY 130 specimens (Table 12).

Two short transverse Ti 6-2-1-.8 SCC tests have just been completed. As shown in Table 13, the crack grew .6 inch in one specimen and 1.1 inches in the other. These results are under investigation.

The crack growth rate behavior of HY 130 as shown in Figure 23, was increased by sea water environment up to 1.7 times the rate in air. This is similar to the results reported by Barson (13) although he found the increase to be by a factor of 2.5.

The differences in crack growth rates between the PH alloys are negligible both in air and sea water. The sea water environment growth rate is approximately double the air growth rate.

For the stress intensity range tested, sea water had no adverse effect on flaw growth rate of Ti 6-2-1-.8.

Future Work

This program will be continued in 1973 to more completely define the role of the individual materials and coating systems in future hydrofoil design.

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